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CONUS assessment of streamflow change in burned watersheds

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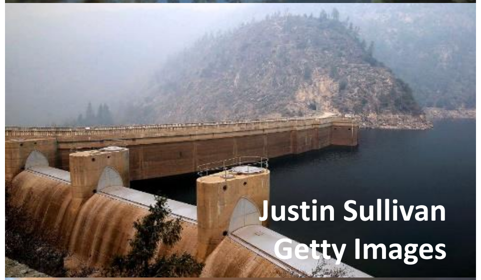
Wildland fire

- Natural disturbance
- Establish natural succession of forests
- Stimulate growth and biodiversity
- Environmental effects (air and water contamination, landslides)
- Increased risk for water resources due to:
  - Longer wildfire seasons
  - Increasing annual area burned
  - More severity fires associated with forest densification
  - Persistent drought
  - Climate change
  - Increasingly populated wildland-urban interface



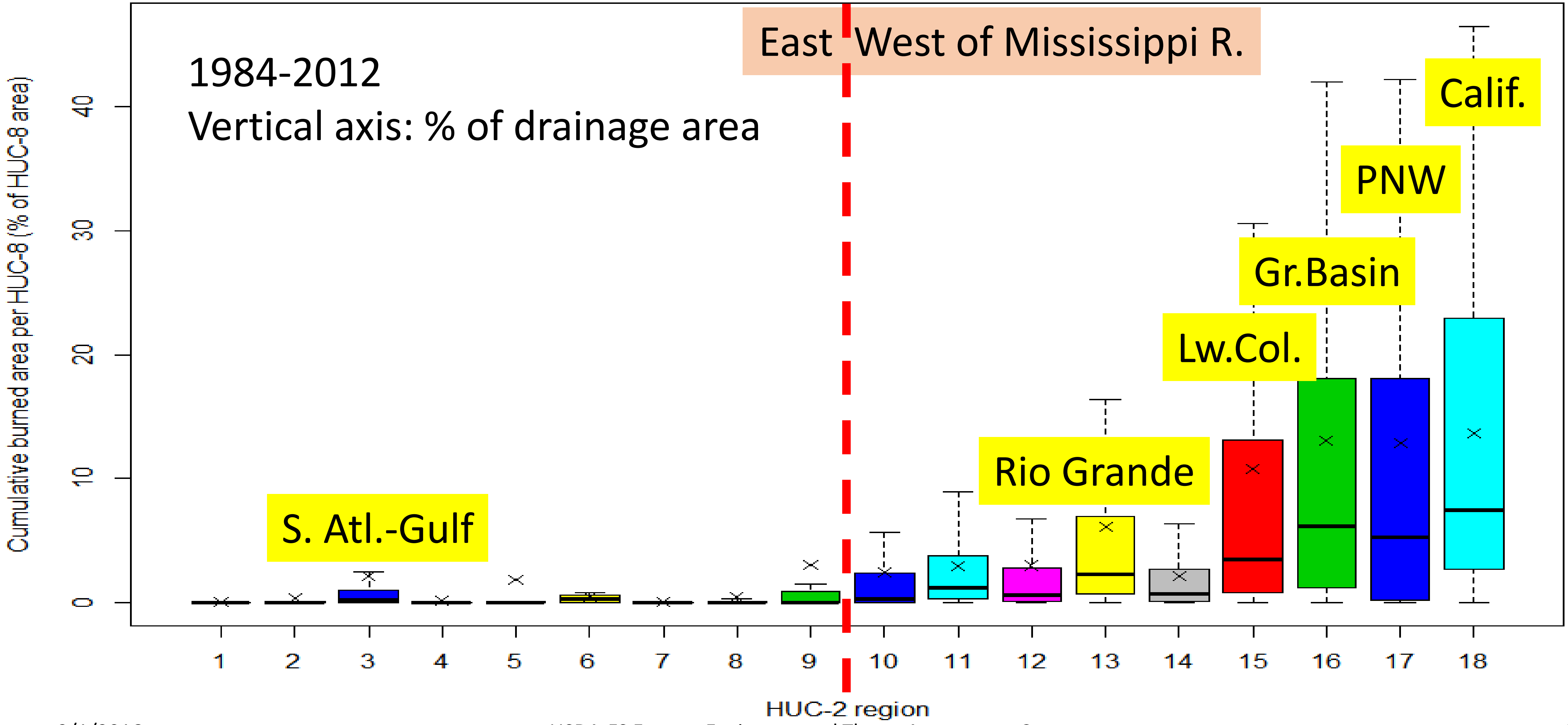
Top 5 wildland fire years (1960-2015)

Year	*Fires*	*Acres*
2015	68,151	10,125,149*
2006	96,385	9,873,745
2007	85,705	9,328,045
2012	67,774	9,326,238
2011	74,126	8,711,367
(YTD)	(40,248)	(560,000)

*Alaska: 5,100,000

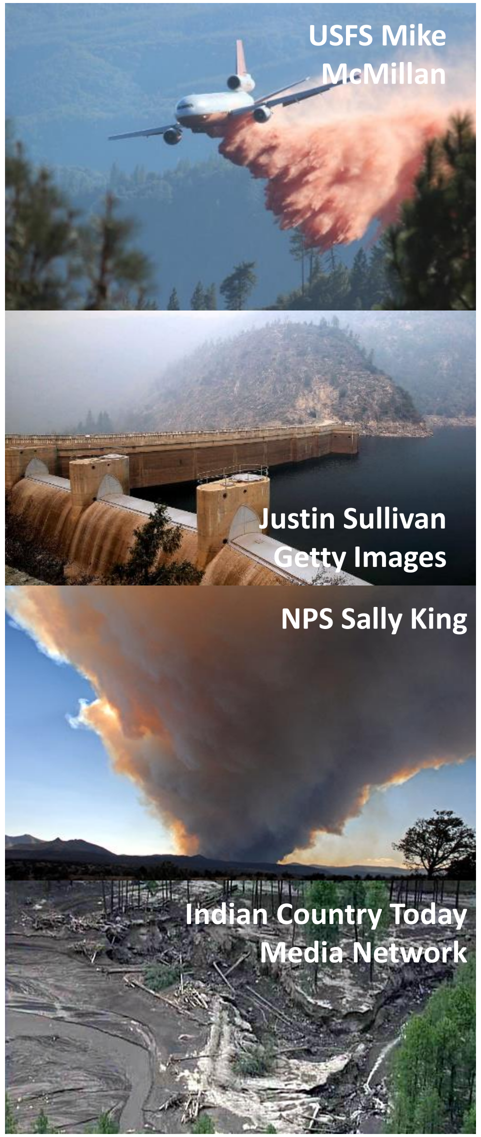
Source: National Interagency Coordination Center

Cumulative burned area per hydrologic region

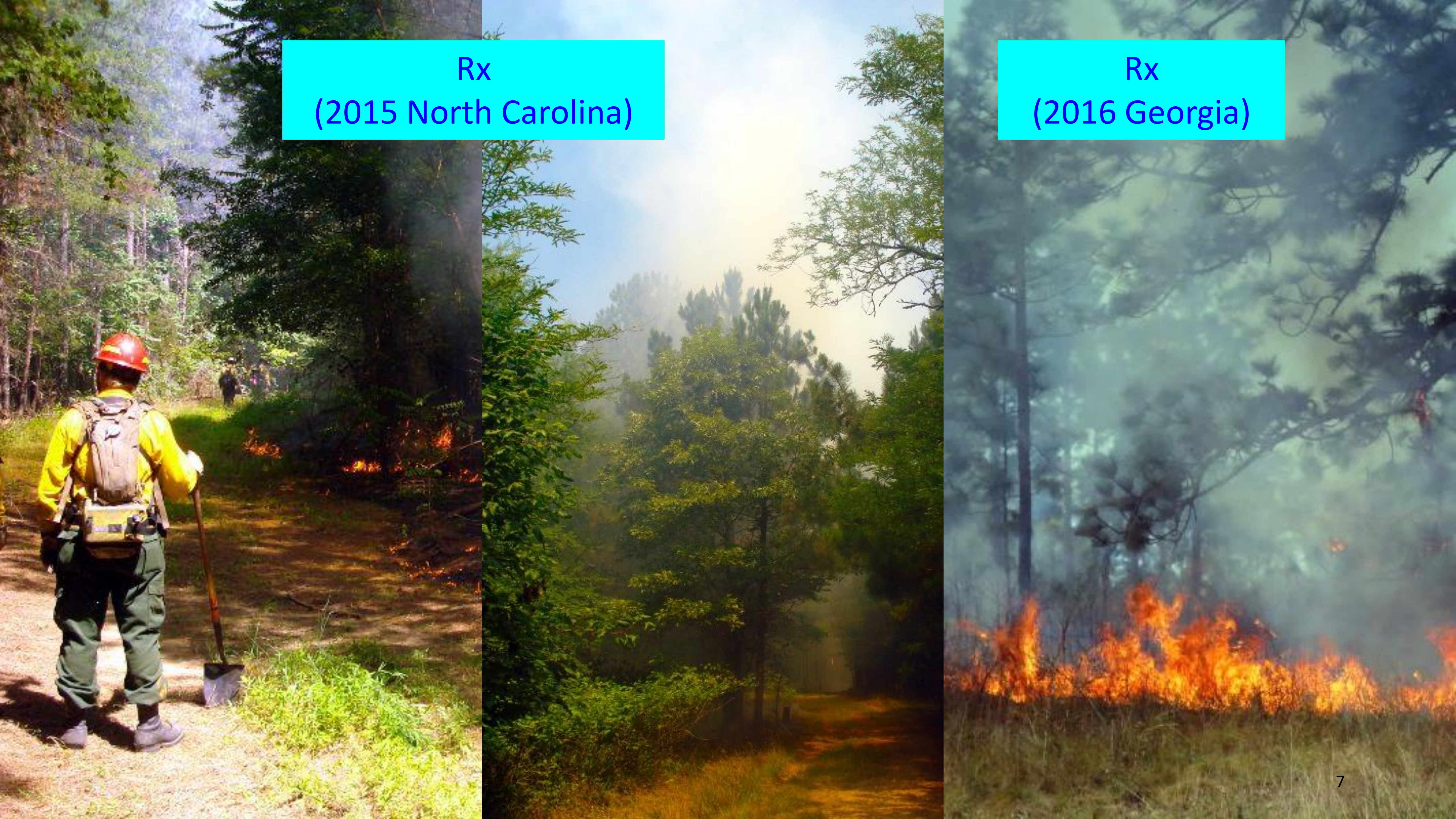


Fire impacts on hydrological processes

- Hillslope initial response
  - Net precipitation ↑
  - Infiltration, ET ↓
  - Runoff ↑
- Depend on vegetation, climate, physical characteristics of watershed (soil, altitude, steepness), water repellency of the soil
- Last up to decades after disturbance and transmitted downstream of hillslope and headwater catchments (importance of *scale*)



Erosion
(2003 Myra Canyon Fire)
Forest recovery
(2009 Terrace Mountain Fire)

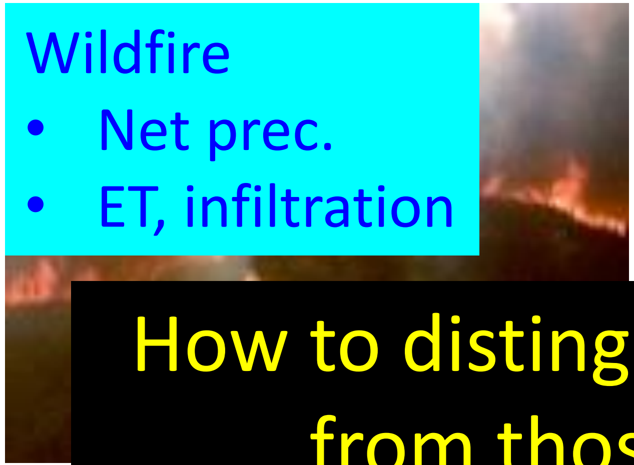

Rx
(2015 North Carolina)
Rx
(2016 Georgia)

Fire impacts in U.S. forests

- 43-66% of freshwater resources originate on forest lands
- National Forests:
  - CONUS average: 18%
  - Mississippi River basin 2-5%
  - Colorado: 70%
  - Western U.S.: 50%
- Potential impacts on ecological communities & aquatic ecosystem health
- Need to understand how wildfires impact peak flows, flash floods, baseflows, annual water yield, and the timing of water availability.

Causes of hydrologic disturbance in forests

Wildfire
- Net prec.
- ET, infiltration

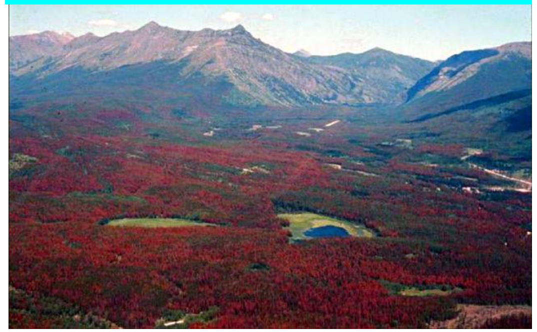


Human activity:
- Withdrawal
- River dams
- Thermal pollution

How to distinguish streamflow changes caused by fire from those caused by variations in climate?

Climate:
- Drought
- Climate oscillations

Biological:
- Invasive species



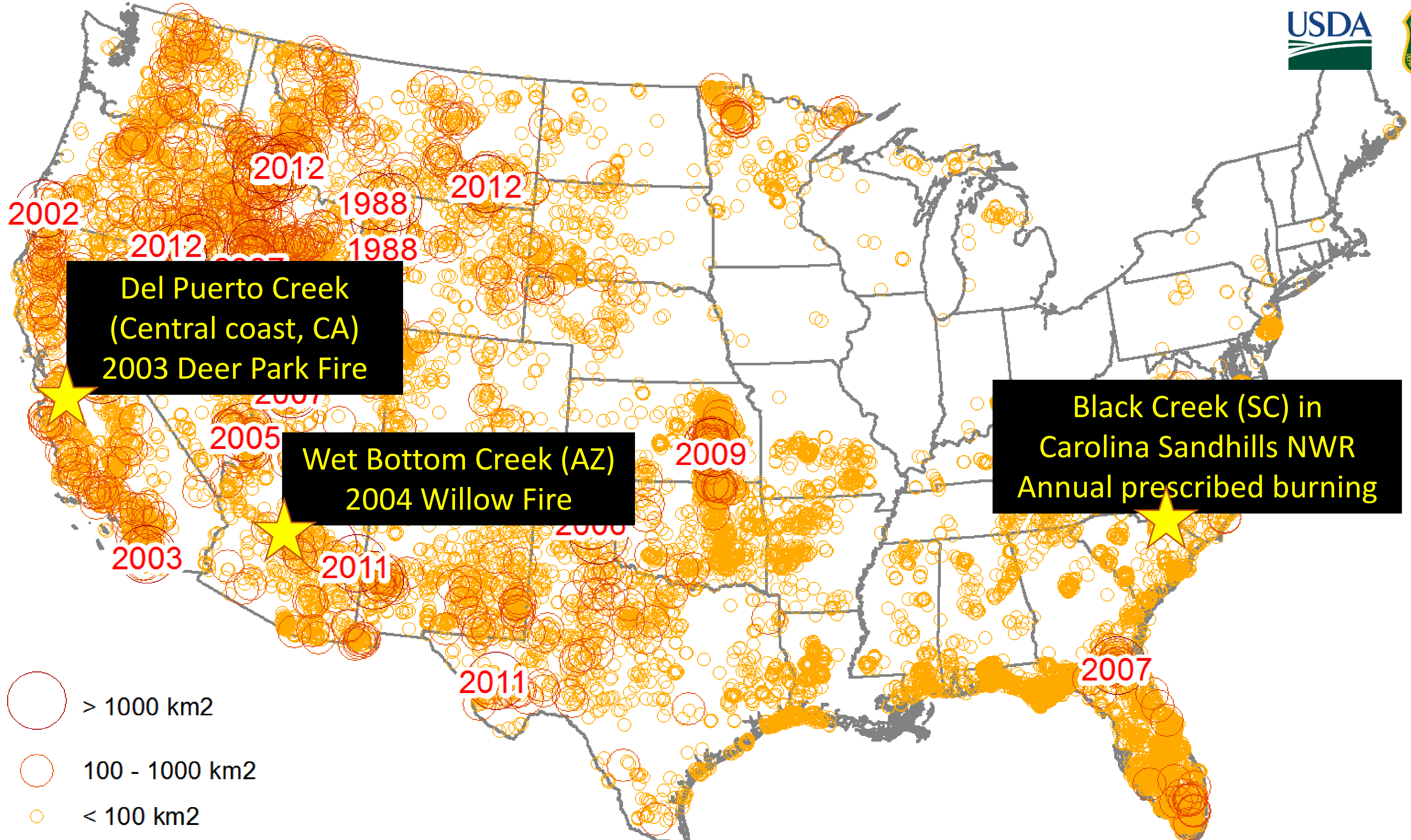
Natural disasters:
- Volcanic eruption
- Erosion and mass movement

Project background

- National Cohesive Wildland Fire Management Strategy (implementation of 2009 Federal Land Assistance Management and Enhancement Act)
  - Assist decision making with regard to prescribed fuel treatments
  - Enhance resilience of forest watersheds
  - Maximize municipal water supplies
- Objective: CONUS assessment of wildland fire impacts (wildfire and prescribed fire) on watershed annual water yields

Outline

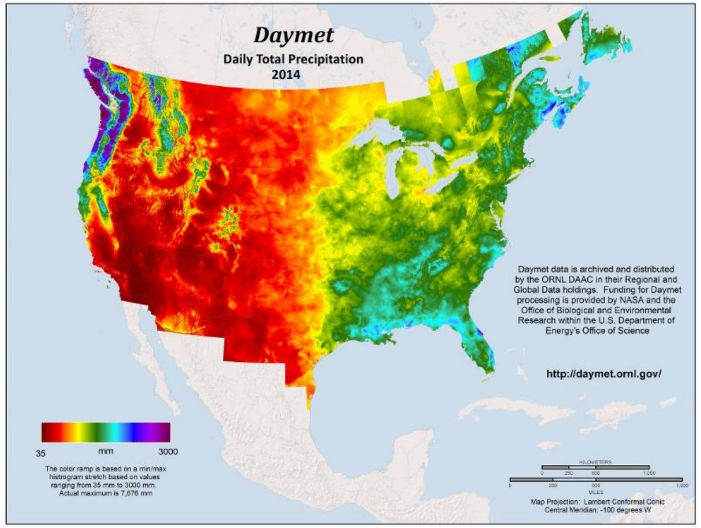
1. Case studies
2. CONUS assessment

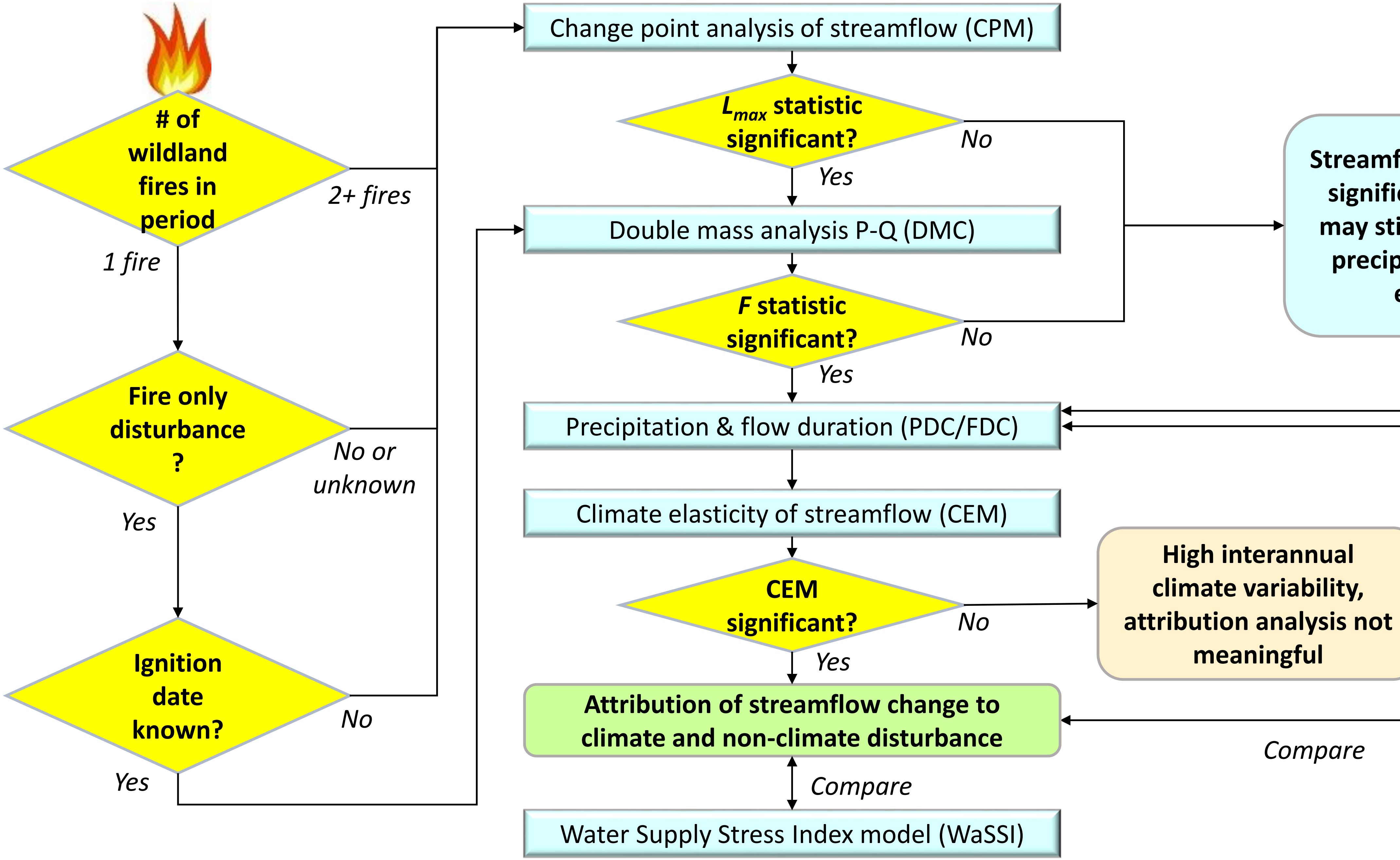


2012
2012
1988
2002
2012
1988
Del Puerto Creek
(Central coast, CA)
2003 Deer Park Fire
2005
Wet Bottom Creek (AZ)
2004 Willow Fire
2009
Black Creek (SC) in
Carolina Sandhills NWR
Annual prescribed burning
2003
2011
2011
2007
> 1000 km2
100 - 1000 km2
< 100 km2

Temporal resolution

Datasets	Spatial resolution	Time resolution	Period
MTBS Burned area and burn severity	30 x 30 m	Annual burn severity maps	1984-
PRISM climate	4 x 4 km	Monthly	1899-
MODIS NDVI	236 x 236 m	Biweekly	2003-
Daymet climate	1 x 1 km	Daily	1980-
USGS GAGES-II streamflow	Point locations	Daily	1900-





# of wildland fires in period
2+ fires
1 fire
Fire only disturbance ?
No or unknown
Yes
Ignition date known?
No
Yes
Change point analysis of streamflow (CPM)
L_{max} statistic significant?
No
Yes
Double mass analysis P-Q (DMC)
F statistic significant?
No
Yes
Streamflow change not significant, however may still deviate from precipitation-based estimate
Precipitation & flow duration (PDC/FDC)
Climate elasticity of streamflow (CEM)
CEM significant?
No
Yes
High interannual climate variability, attribution analysis not meaningful
Attribution of streamflow change to climate and non-climate disturbance
Compare
Compare
Water Supply Stress Index model (WaSSI)

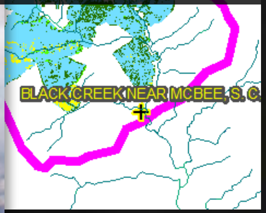
3 watersheds

- 1 - Unburned/Underburned to Low Burn Severity
- 2 - Low Burn Severity
- 3 - Moderate Burn Severity
- 4 - High Burn Severity
- 5 - Increased Greenness/Increased Vegetation

Black Creek (SC)
44 prescribed fires since 2004

- Rx since ~1940s or earlier
- 40% burned since 1984
- Low burn severity
- Drains 114 sq miles
- 30-yr annual P=1144 mm
- PET=981mm
- Runoff 379mm (32%)

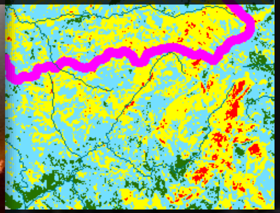
Prescribed burn at Carolina Sandhill NWR



Wet Bottom Creek (AZ)
2004 Willow Fire

- 75% burned
- Low/moderate severity
- Drains 36 sq miles
- Annual P=473mm
- Snowfall 220-300mm
- PET=873mm
- Runoff 112mm (21%)

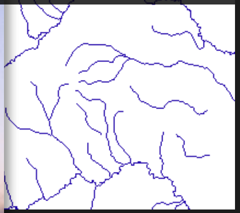
Photo: Arizona Fire Tracker



Del Puerto Creek (CA)
2003 Deer Park Fire

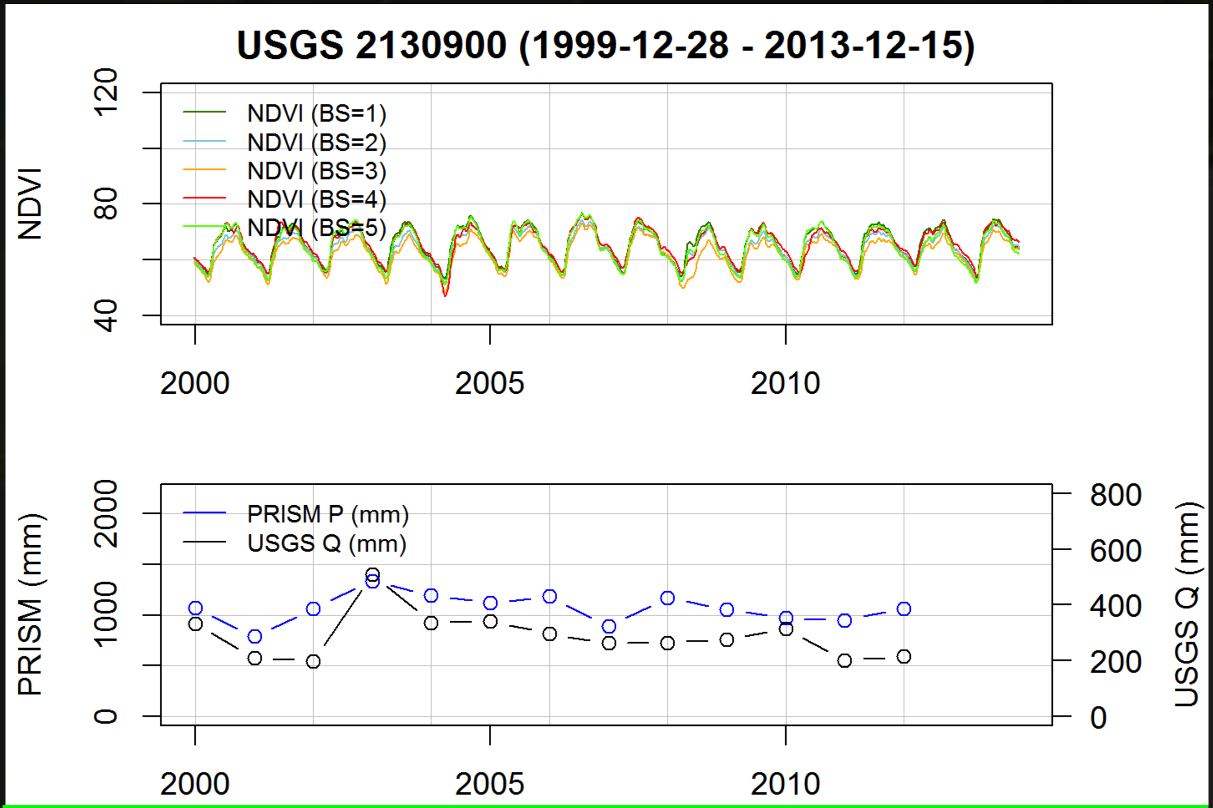
- 30% burned
- Moderate/high severity
- Drains 72 sq miles
- Intermittent flow regime
- Annual P=418mm
- PET=904mm
- Runoff 41 mm (8%)

2007 Lick Fire Photo: George Gray



Comparison of 3 watersheds

Black Creek (SC)
44 prescribed fires since 2004



Prescribed burns are performed annually, not much interannual variability NDVI

Comparison of 3 watersheds

Wet Bottom Creek (AZ)
2004 Willow Fire

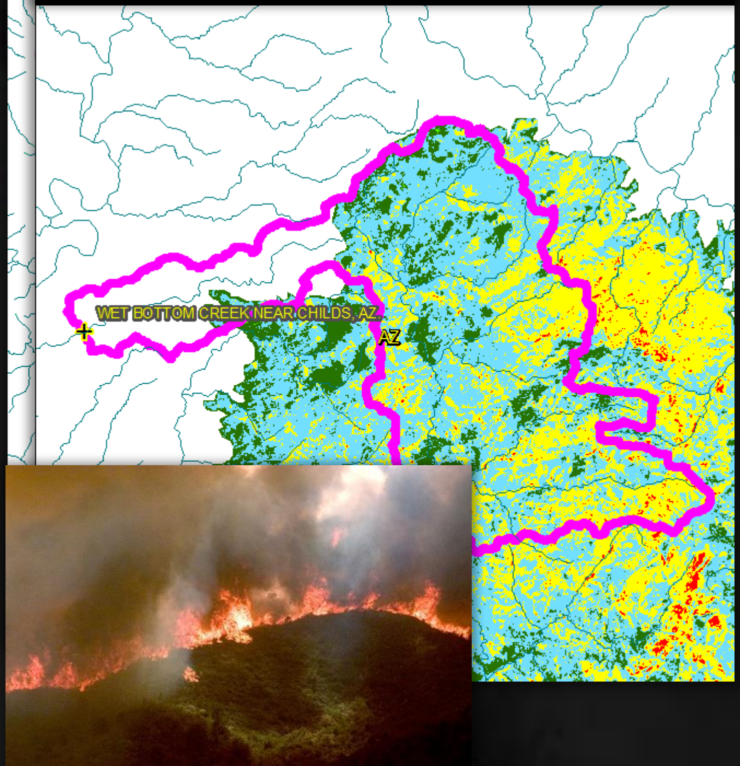
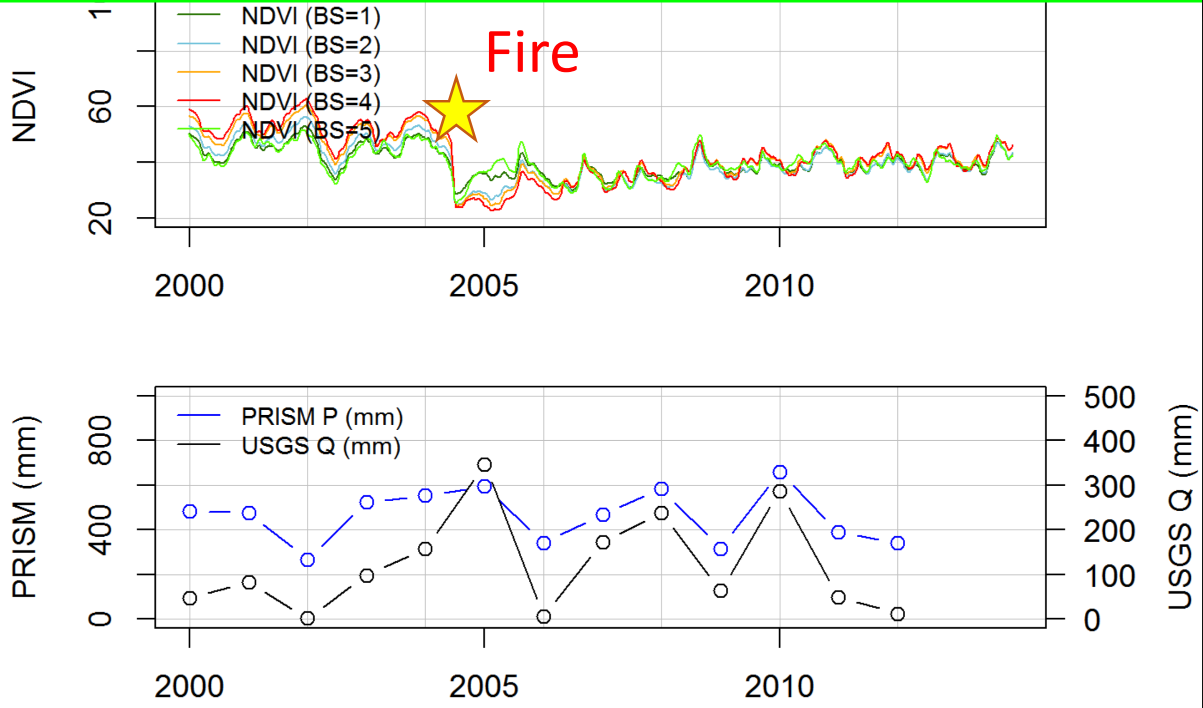


Photo: Arizona Fire Tracker

Gradual post-fire recovery NDVI (typical)

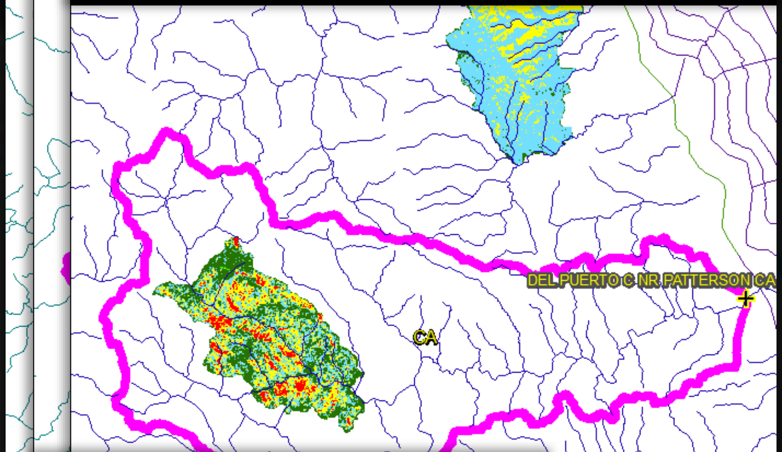


Comparison of 3 watersheds

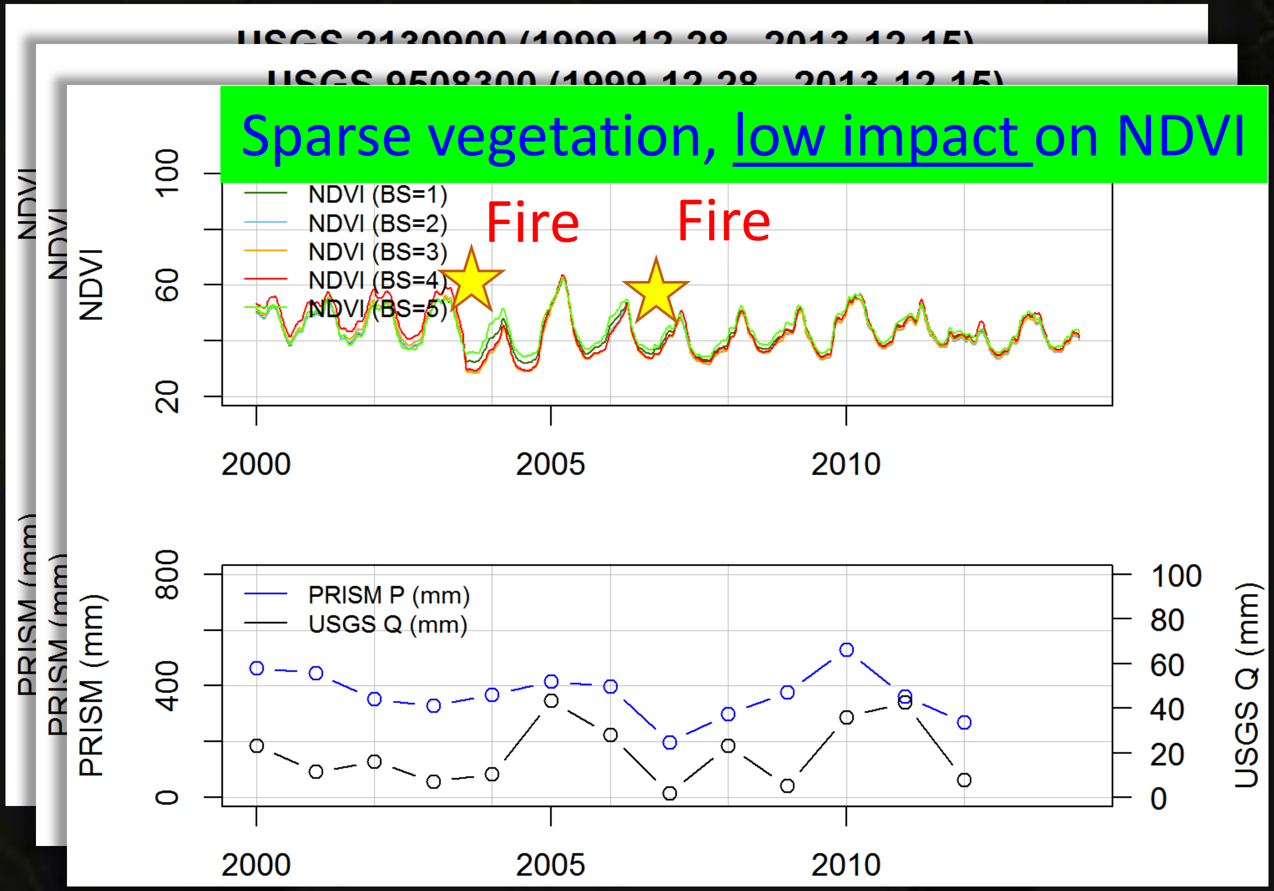
Black Creek (SC)

Wet Bottom Creek (AZ)

Del Puerto Creek (CA)
2003 Deer Park Fire

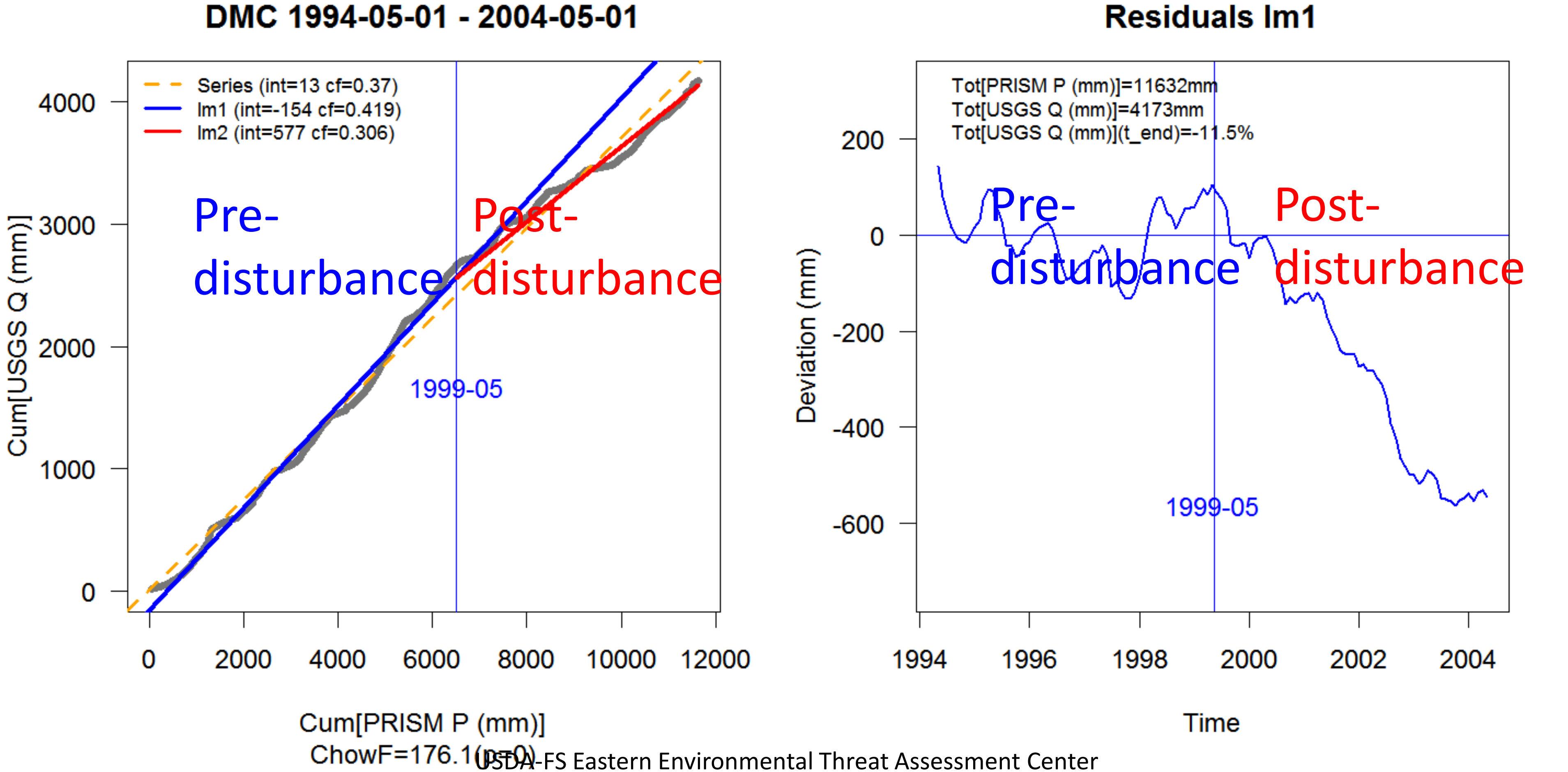


2007 Lick Fire Photo: George Gray



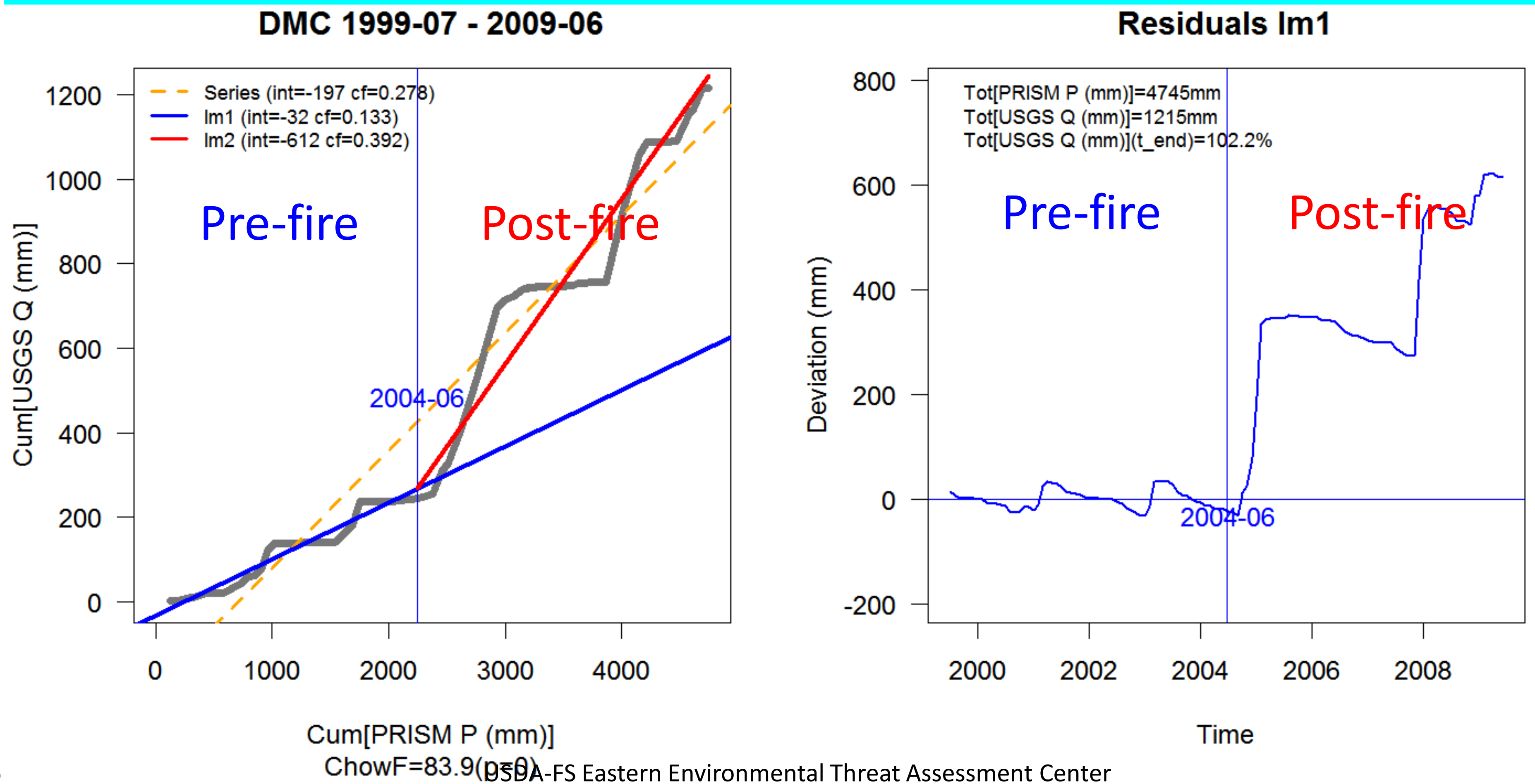
Black Creek (SC) / Prescribed burning

Double mass streamflow vs. precipitation: <u>streamflow lower than predicted</u> based on precipitation after 1998 (p<0.01)



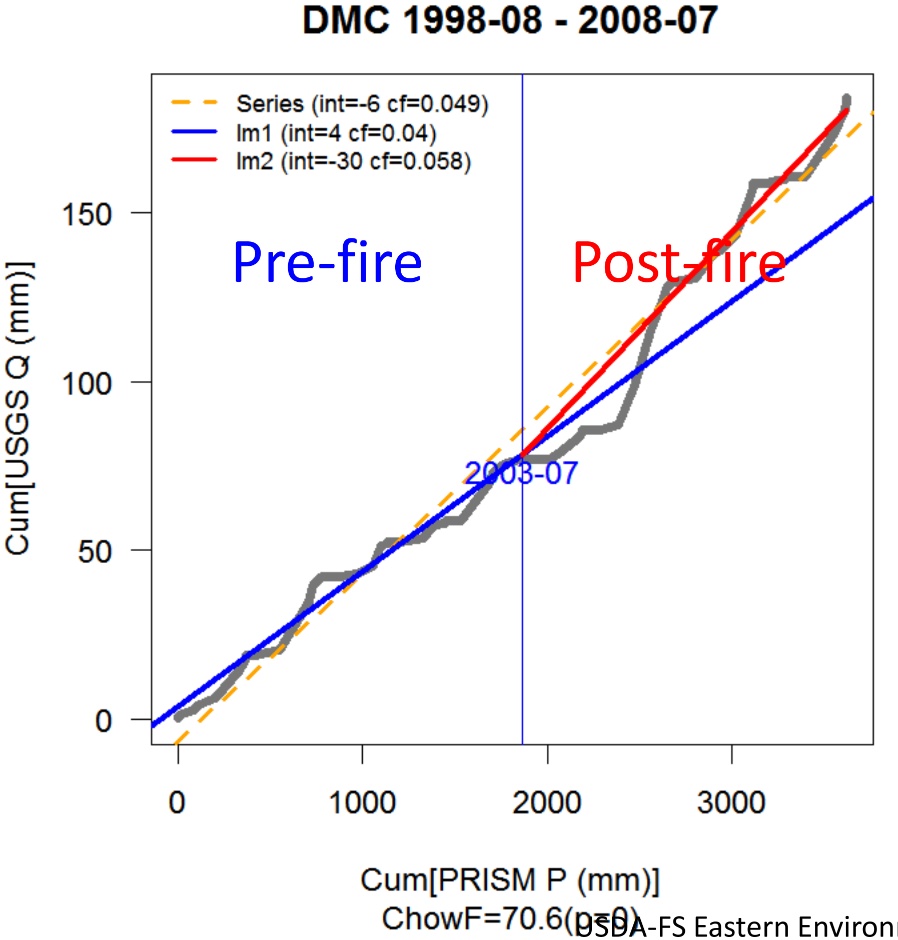
Wet Bottom Creek (AZ) / 2004 Willow Fire

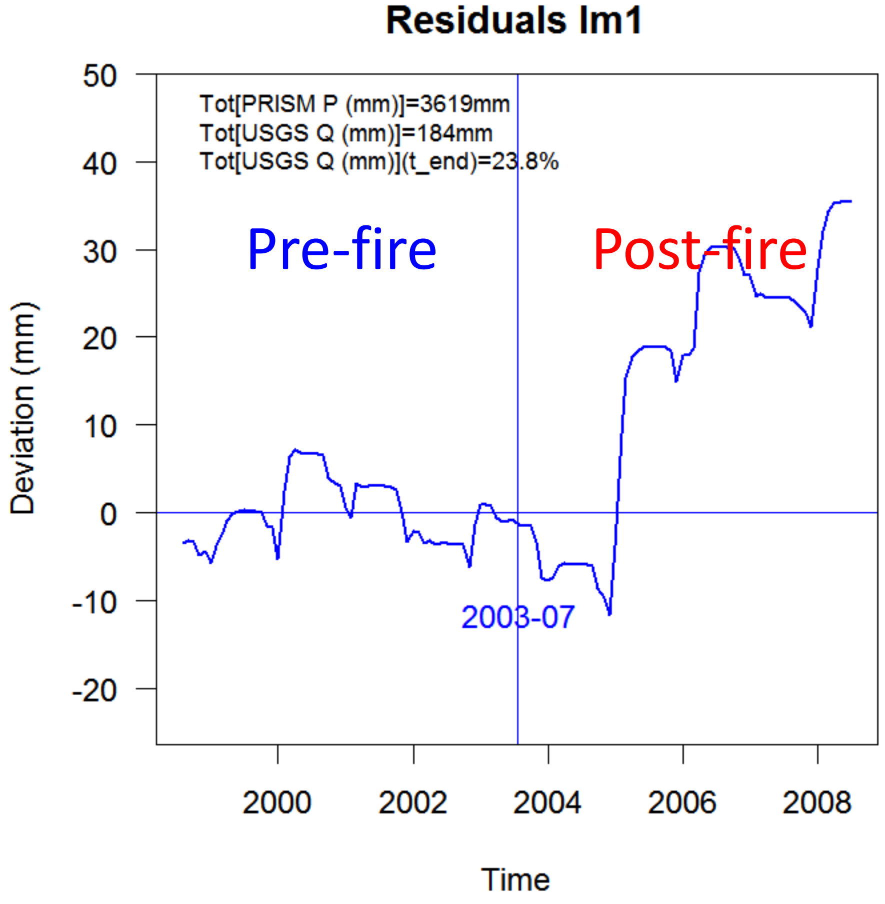
Double mass: streamflow in post-fire snowmelt season much higher than predicted based on precipitation ($p<0.01$)



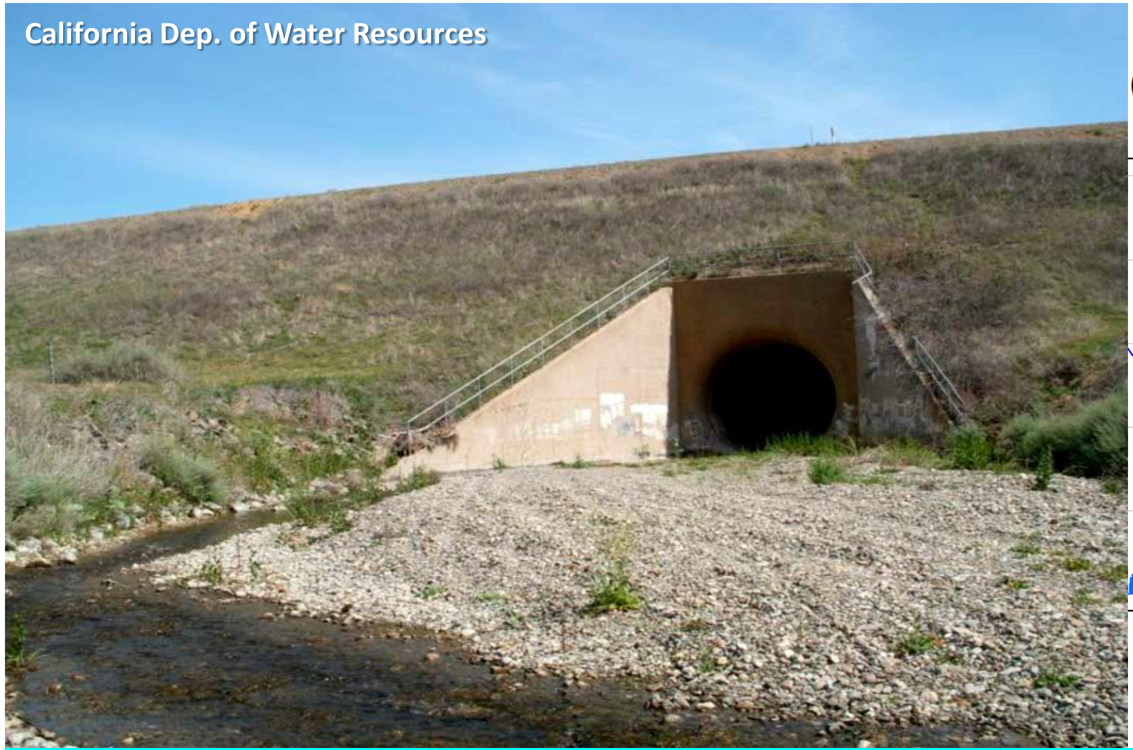
Del Puerto Creek (CA) / 2003 Deer Park Fire

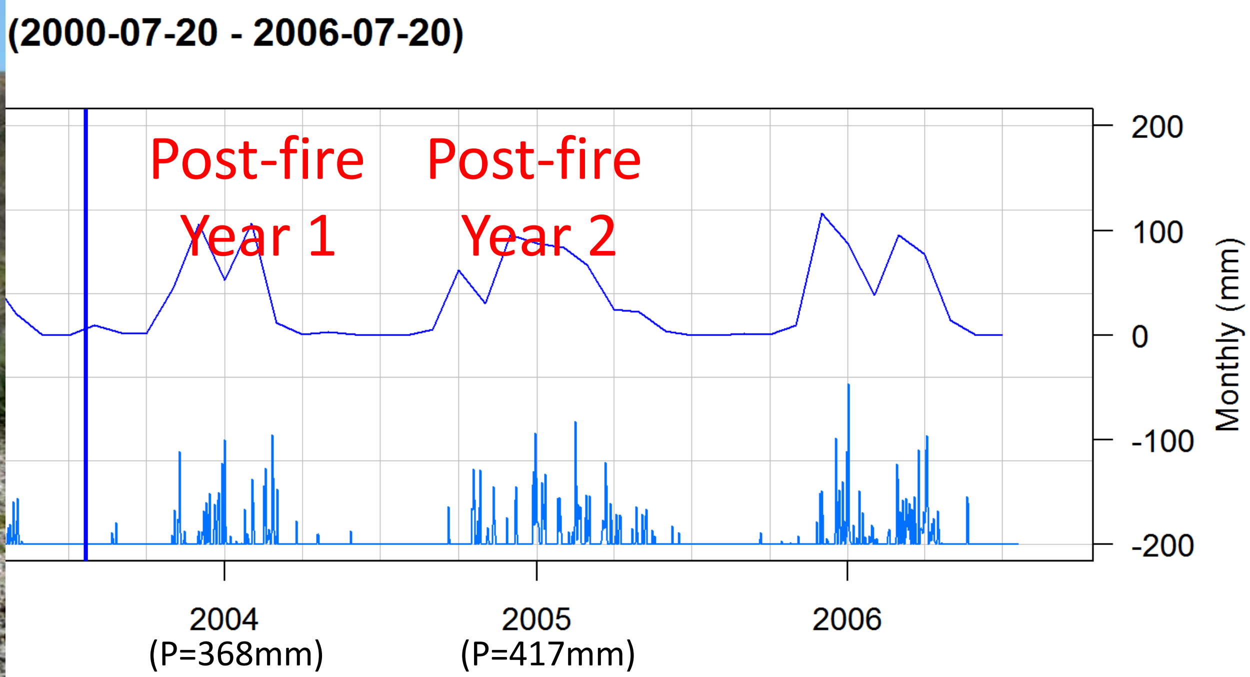
Double mass: Delayed response: <u>streamflow in post-fire year 2 higher</u> than predicted based on precipitation (p<0.01)





Del Puerto Creek (CA) / 2003 Deer Park Fire





Delayed response explained by more wet days during <u>winter post-fire year 2</u>

<u>Significant increase in stream flow and erosion</u>

Attribution of annual streamflow change

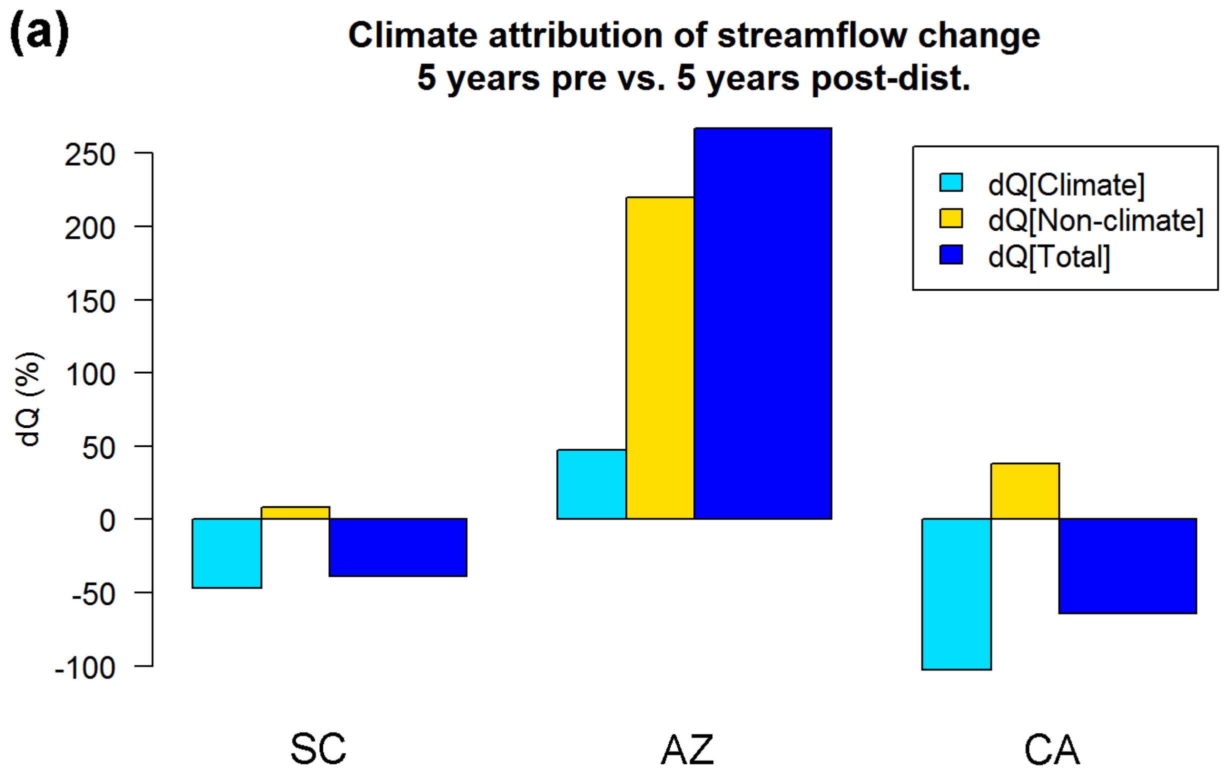
1. Climate elasticity model (CEM) = Predict *dQ* given *dP*
2. Rainfall runoff or reservoir model (RRM) = Predict *Q* given *P*

Attribution of annual streamflow change

$$\Delta Q = \Delta Q_{climate} + \Delta Q_{disturbance}$$

1. Define CEM and RRM (Bayesian Information Criterion)
2. Predict $\Delta Q_{climate}$ for post-fire period
3. $\Delta Q_{disturbance} = \Delta Q - \Delta Q_{climate}$

Attribution of annual streamflow change

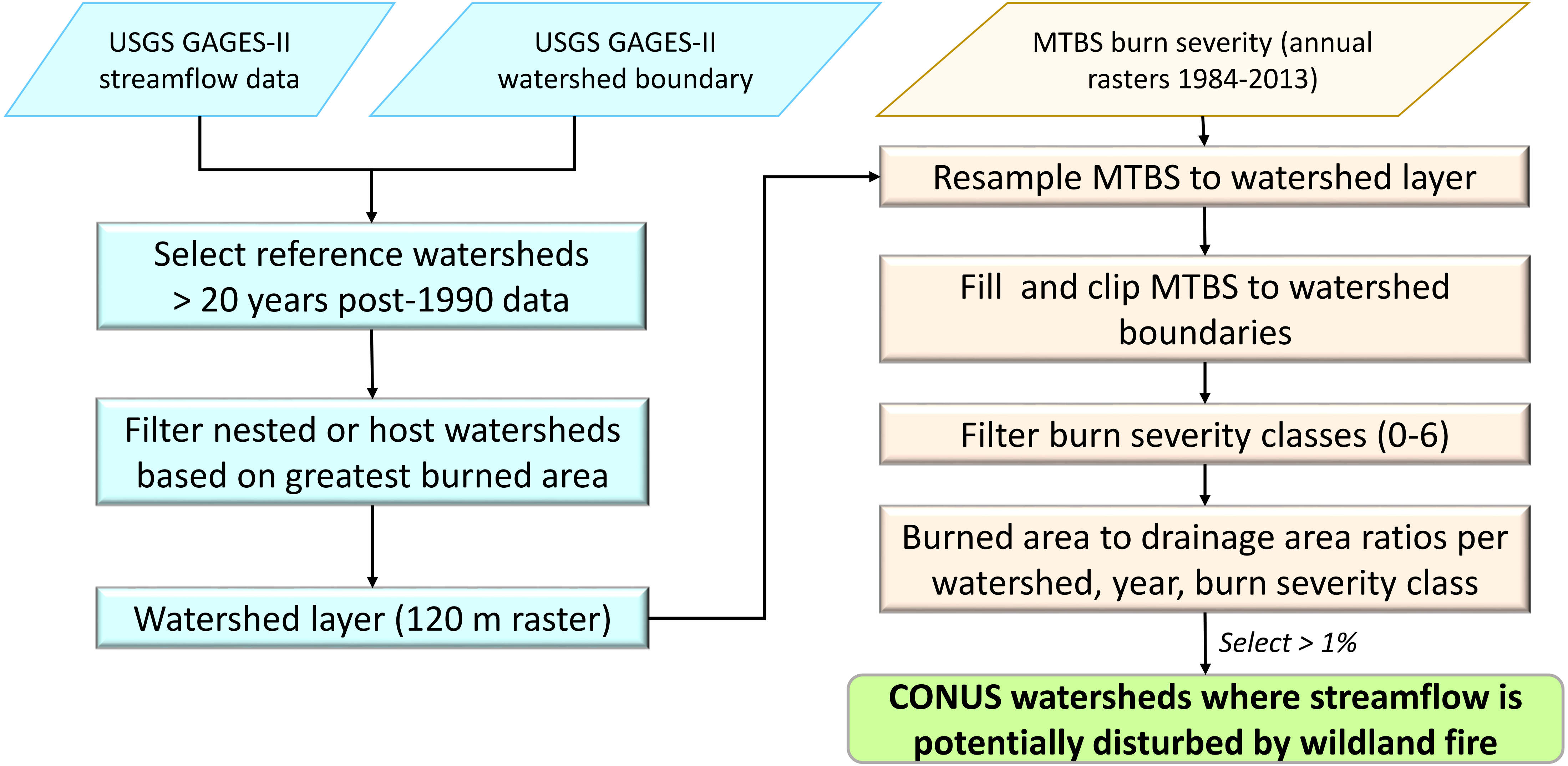


- S.C. 5-year yield -38.5% due to climate, Rx effect very small
- Ariz. 5-year yield +266.9%, principally due to disturbance effects (213.4%)
- Cal. 5-year yield +10.6%, where disturbance effects (yield impact +18.1%) was attenuated by climate trends (yield impact -7.6%)

Outcomes case study

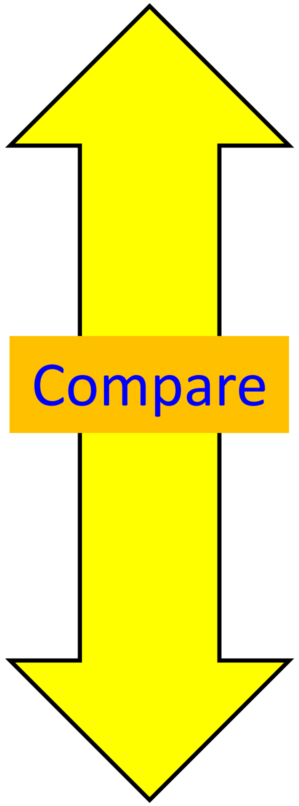
- Regional climate patterns amplify (Ariz.) or attenuate (Cal.) the post-fire yield increase
- Post-fire floods can first occur up to several years after fire disturbance in dry watersheds (Cal.)
- Yield change not attributed to prescribed burning, likely caused by very wet winter and storm damage (S.C.)

Identify burned watersheds

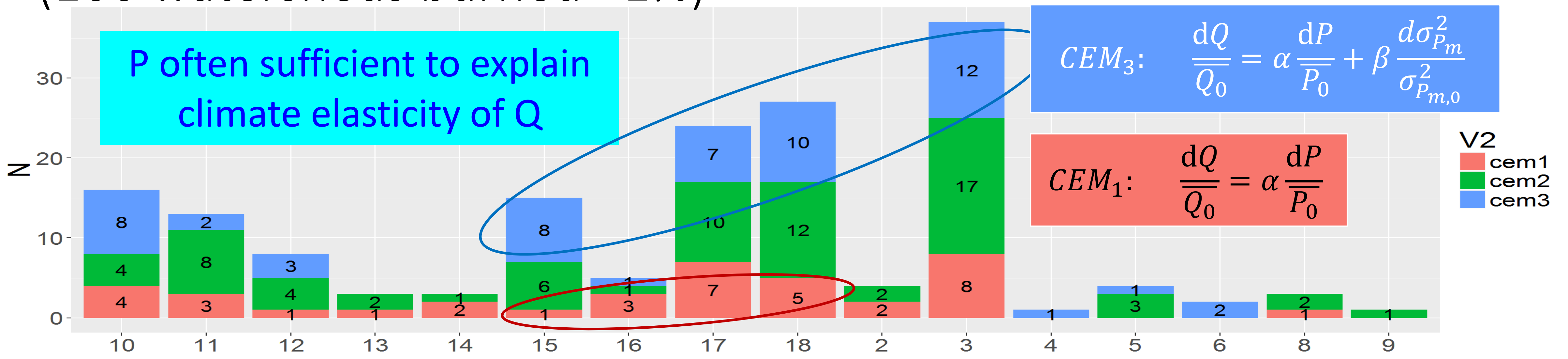


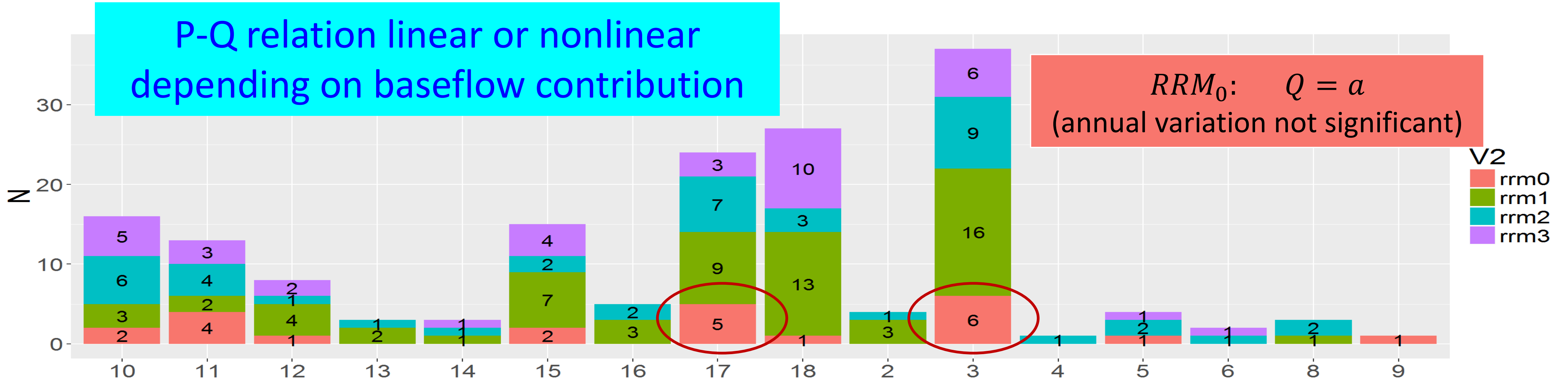
Attribution of annual streamflow change

Climate elasticity models (CEMs)			Rainfall-runoff models (RRMs)		
CEM_0:	$\frac{dQ}{\overline{Q_0}} = 0$	(ref.)	RRM_0:	$Q = a$	(reference)
CEM_1:	$\frac{dQ}{\overline{Q_0}} = \alpha \frac{dP}{\overline{P_0}}$		RRM_1:	$Q = a + bP$	(lin. reservoir)
CEM_2:	$\frac{dQ}{\overline{Q_0}} = \alpha \frac{dP}{\overline{P_0}} + \beta \frac{dPET}{\overline{PET_0}}$		RRM_2:	$Q = a\, e^{(bP)}$	(nonlinear res.)
CEM_3:	$\frac{dQ}{\overline{Q_0}} = \alpha \frac{dP}{\overline{P_0}} + \beta \frac{d\sigma^2_{Pm}}{\sigma^2_{Pm,0}}$		RRM_3:	$Q = a\, e^{(bP\, \sigma^2_{Pm})}$	(nonlinear res.)

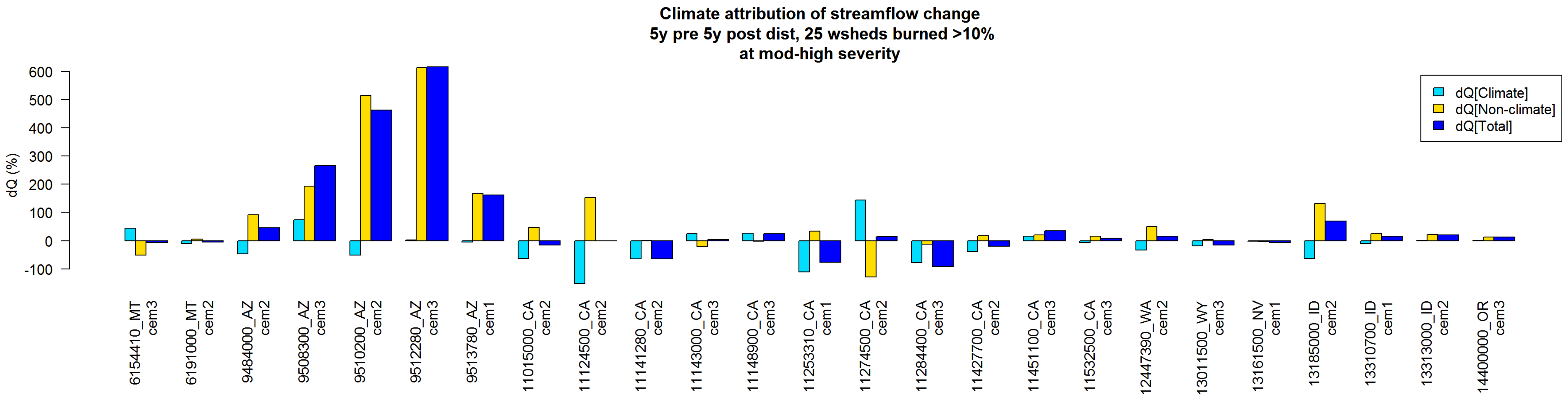


CEM/RRM selections per hydrologic region (166 watersheds burned >1%)

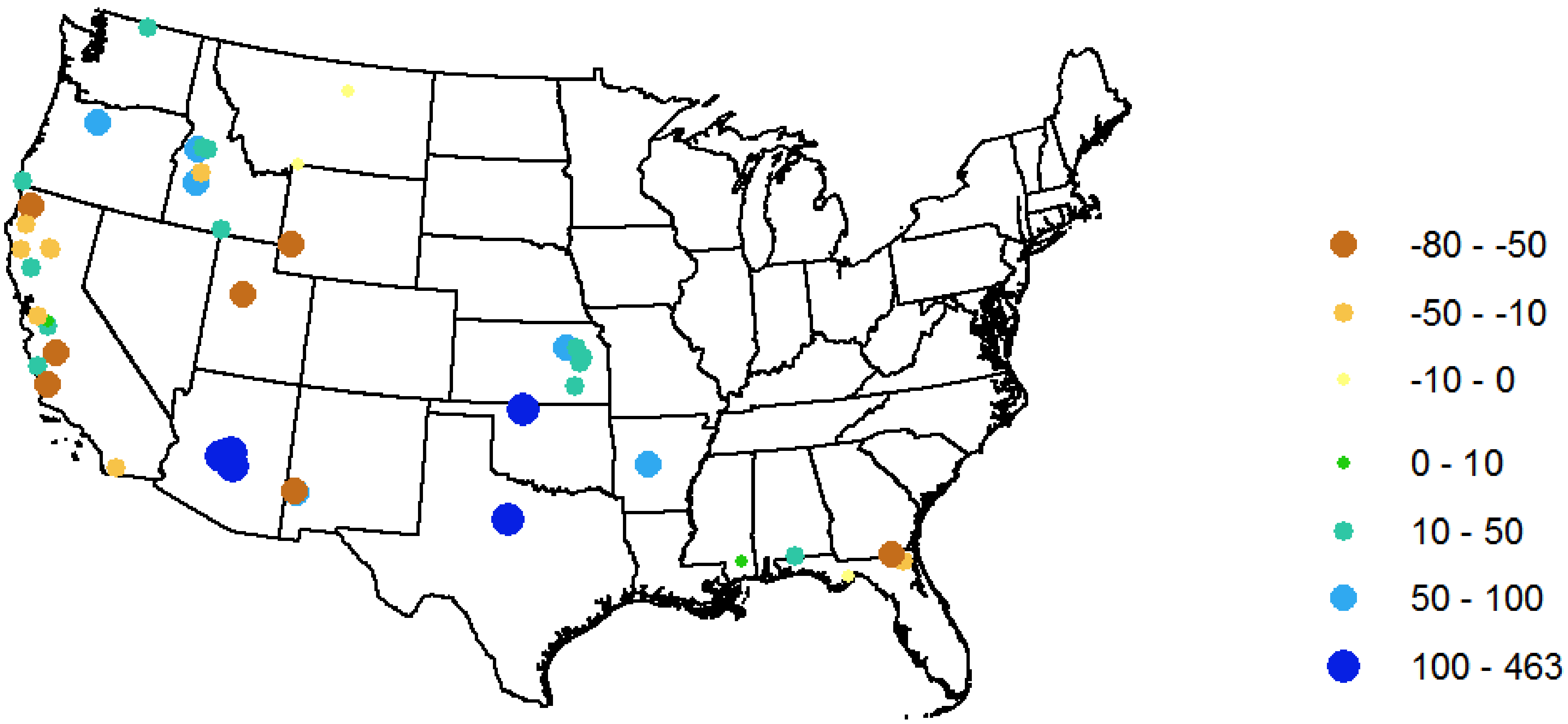




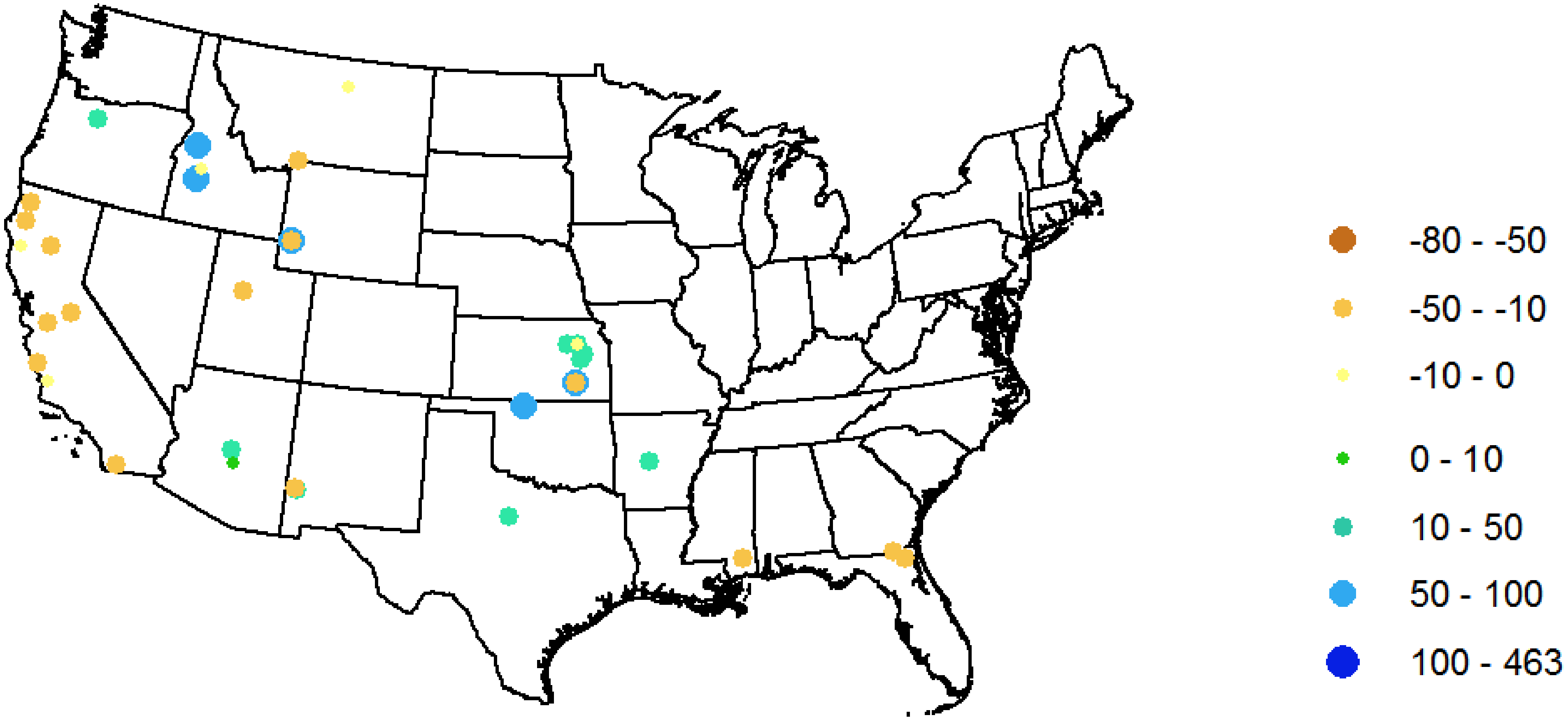
Attribution of annual streamflow change (25 watersheds burned >10%, mod-high severity)



% Observed change annual Q (5y post vs. pre wildland fire)

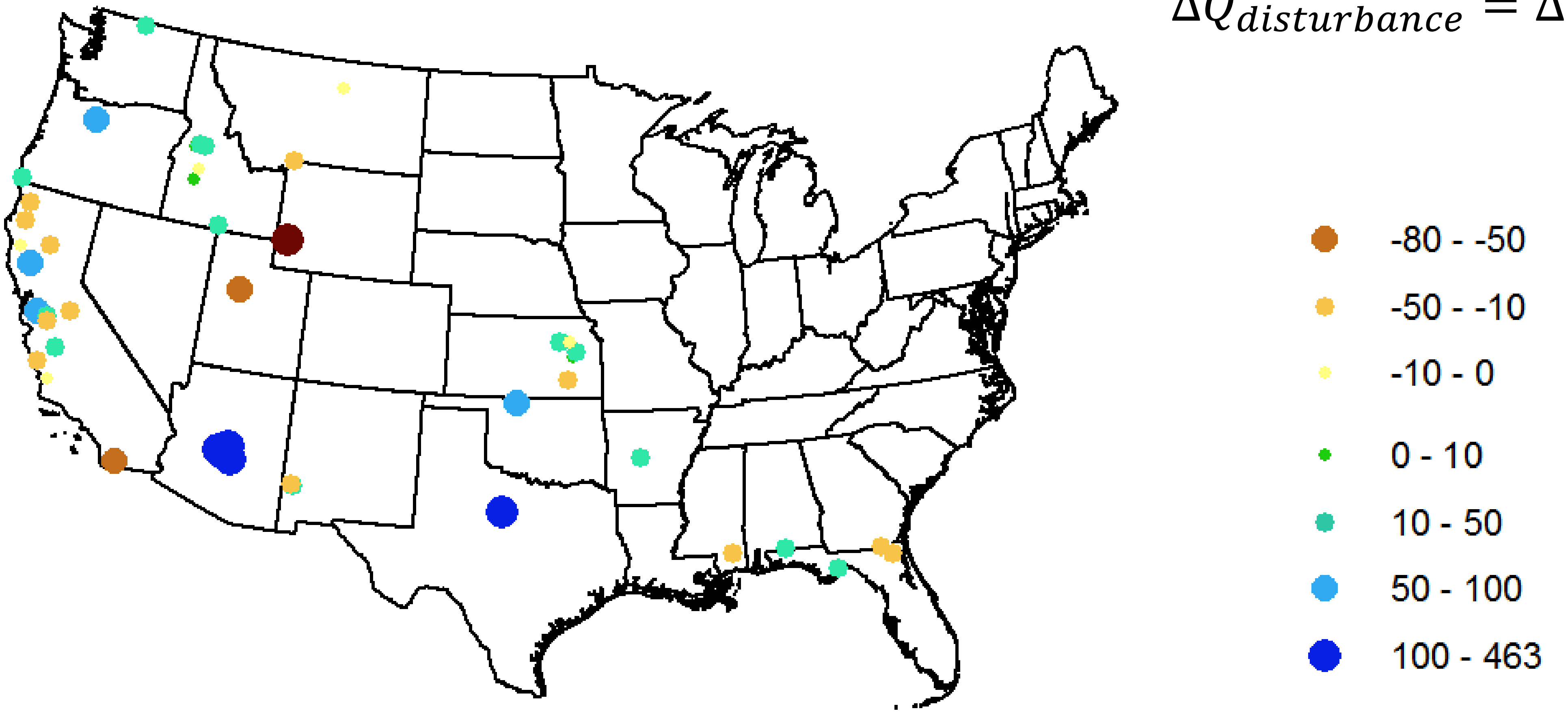


Climate contribution



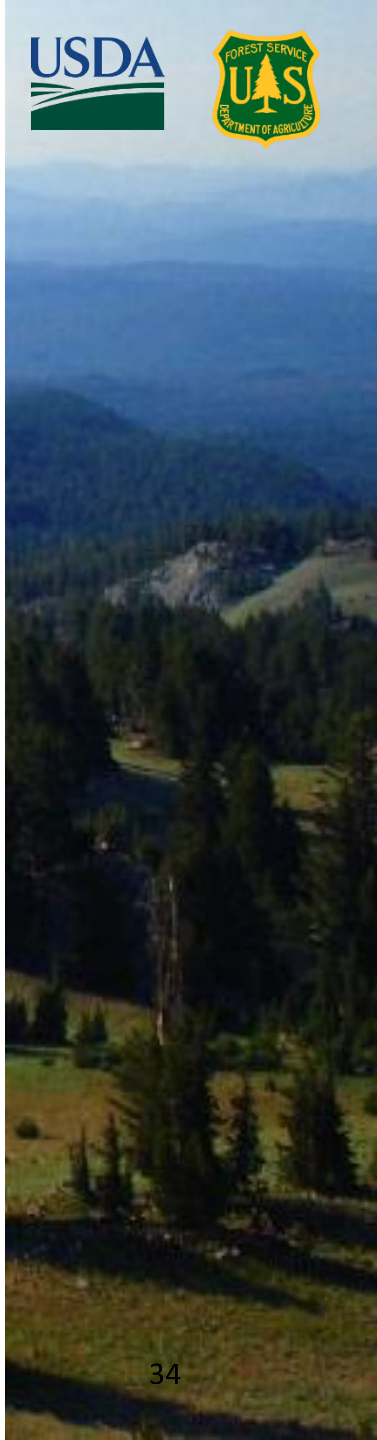
Contribution of fire disturbance

$$\Delta Q_{disturbance} = \Delta Q - \Delta Q_{climate}$$



Outcomes CONUS assessment

- Flow increased (57 watersheds), decreased (68), or remained unchanged (44)
- Median dQ (MdQ) -12% in 62 watersheds with a burned area to drainage area ratio (BAR) <10%, due to lower annual P (-16%) associated with regional climate trends, a common response in watersheds in the eastern states with low severity *Rx* or WF
- *MdQ* +11% in 44 watersheds with BAR >10%, notwithstanding overall declining *P*. Mainly located in W. CONUS, where *dQ* was correlated with PET (R^2=0.73) and burn severity (R^2>0.53)
- Most severe impacts: Arizona (2005 Cave Creek Complex, 2004 Edge Complex and 2004 Willow Fires), with BARs >39% and *dQ*>+160%



Outcomes CONUS assessment

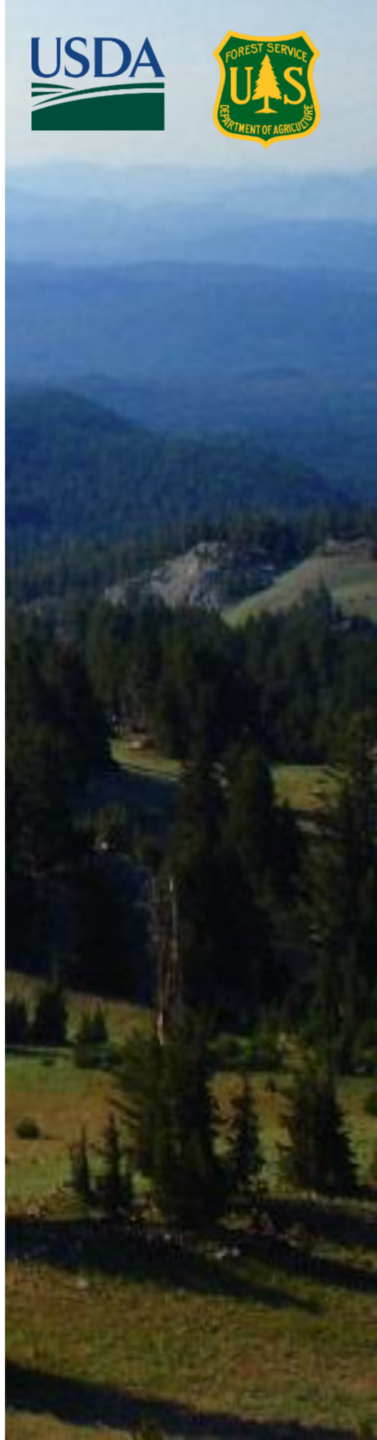
- Clear regional patterns in post-fire *Q*
- Downward trends in *P* can mask flow enhancing effects

Seminar highlights

- Forests are indispensable water resource areas
- Wildland fire disturbance and climate variability both affect streamflow and water yields
- Distinguish between fire and climate impacts using high-resolution hydrological data and local climate models

Perspectives

- Tool development
  - Simulate wildland fire and fuel management impacts on infiltration and ET (MIKE SHE) for priority watersheds
  - Integrate parameterization into the WaSSI water supply stress index model
- Municipal and HUC-8 scale assessment



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Hallema *et al.*, 2016. Assessment of wildland fire impacts on watershed annual water yield: Analytical framework and case studies in the United States. *Ecohydrology*, in revision.

Hallema *et al.*, 2016. Surface storm flow prediction on hillslopes based on topography and hydrologic connectivity. *Ecological Processes,* in press.

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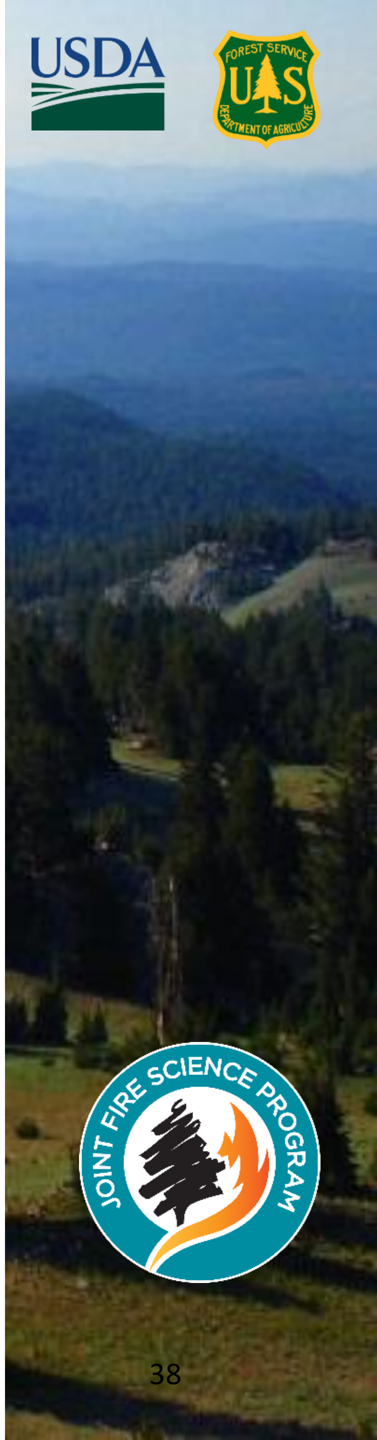
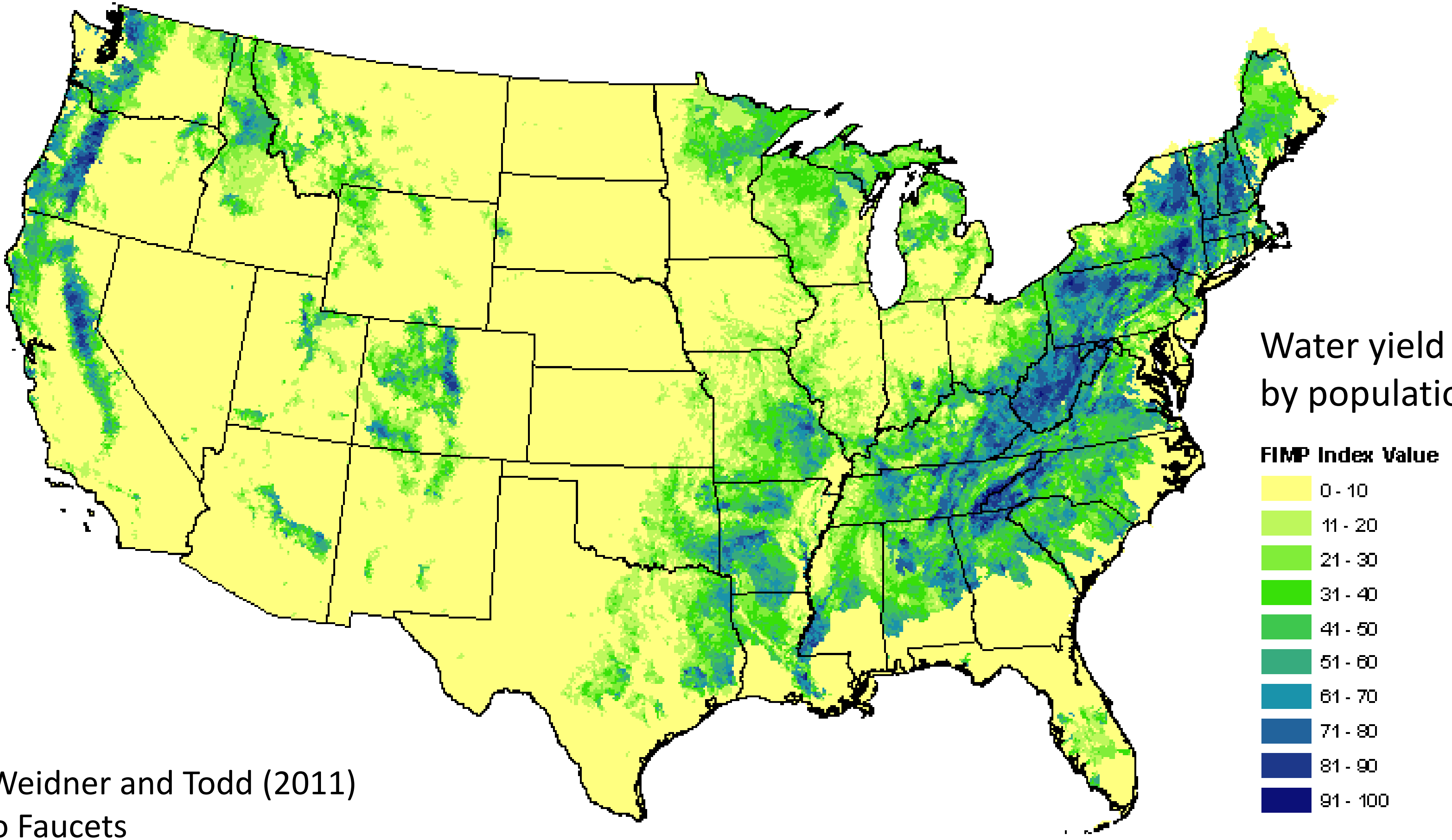


Forest importance to surface drinking water (FIMP)



Water yield weighted by population served

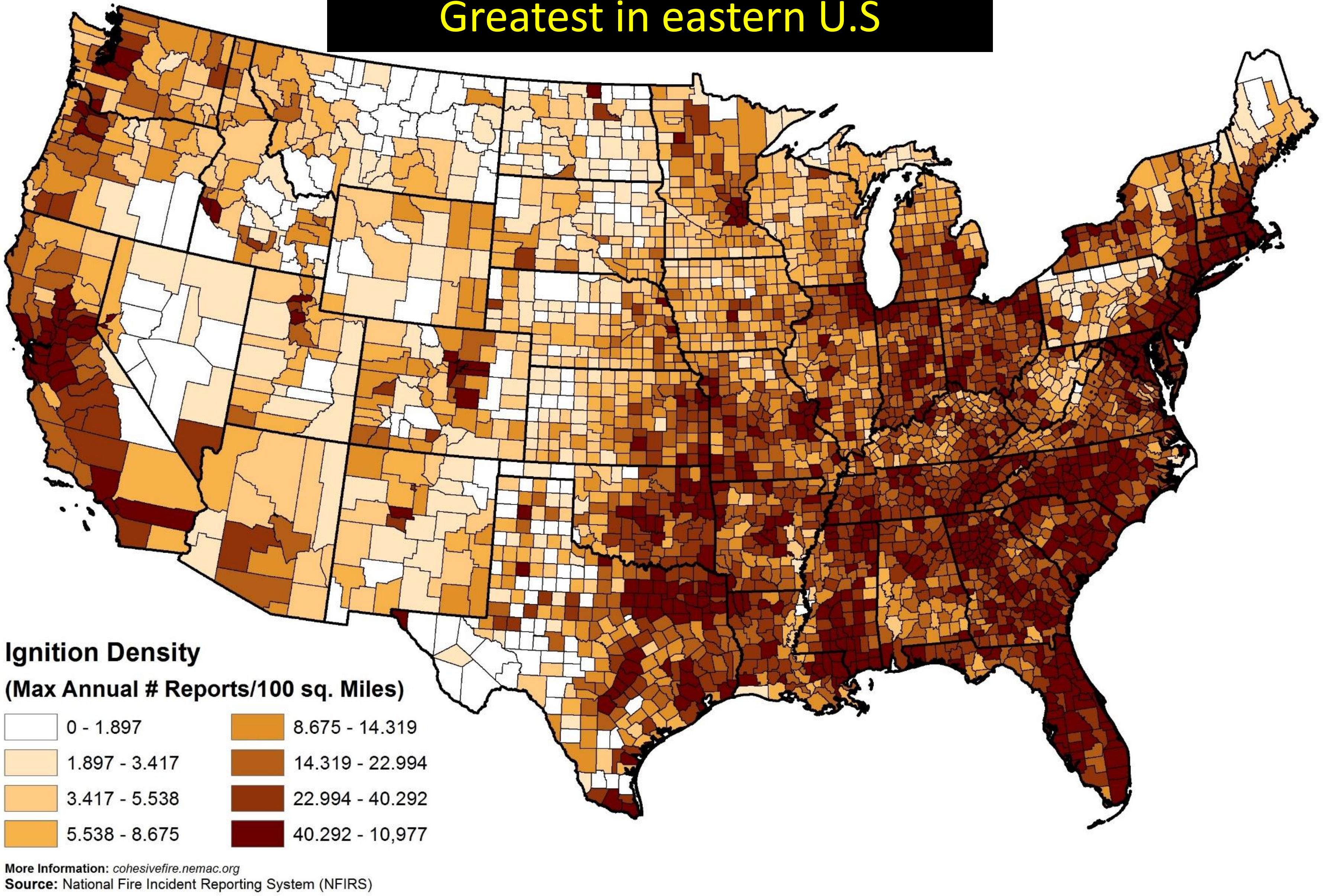
Figure credit: Weidner and Todd (2011)
USFS Forests to Faucets

Fire regimes

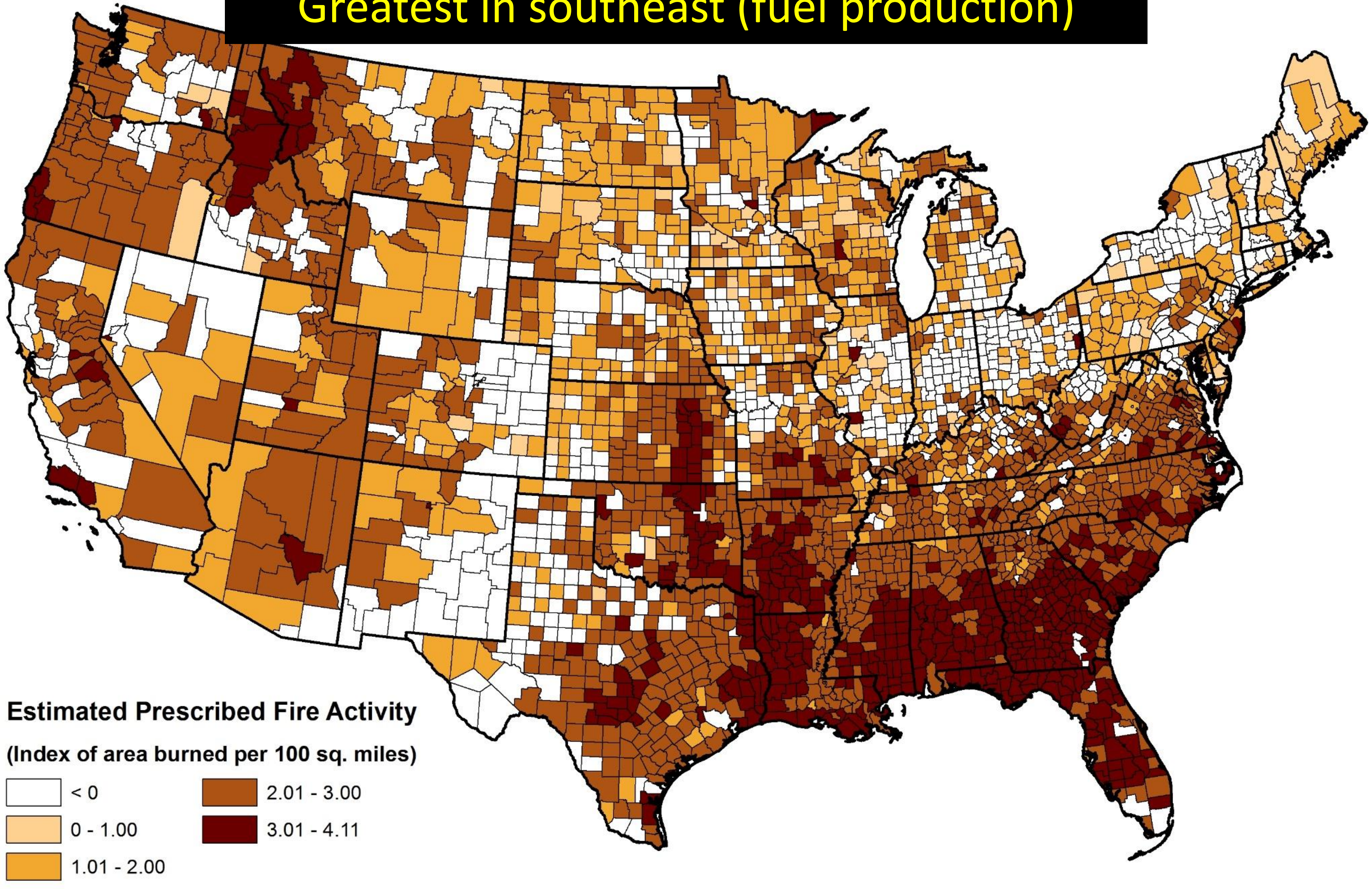
Based on: fire extent, spread pattern, intensity, severity, depth of burn, recurrence interval, and season

1. Understory – Lethal ~20%, structure intact
2. Mixed – Varies with terrain, fuel and weather
3. Stand replacement – Lethal ~80%, crown fires

Max. annual ignitions 2002-2011
Greatest in eastern U.S

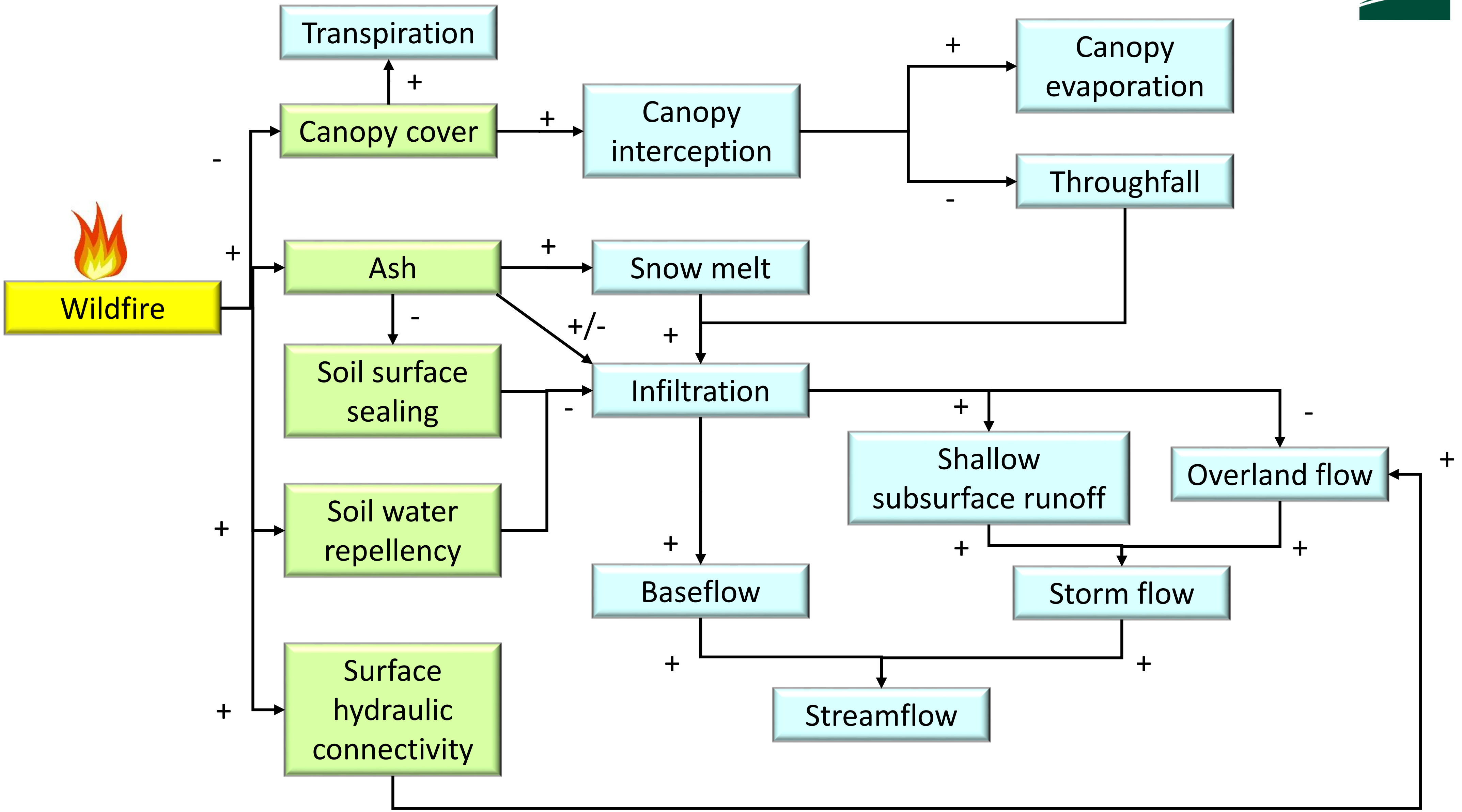


Estimated prescribed fire activity 2008-2011
Greatest in southeast (fuel production)



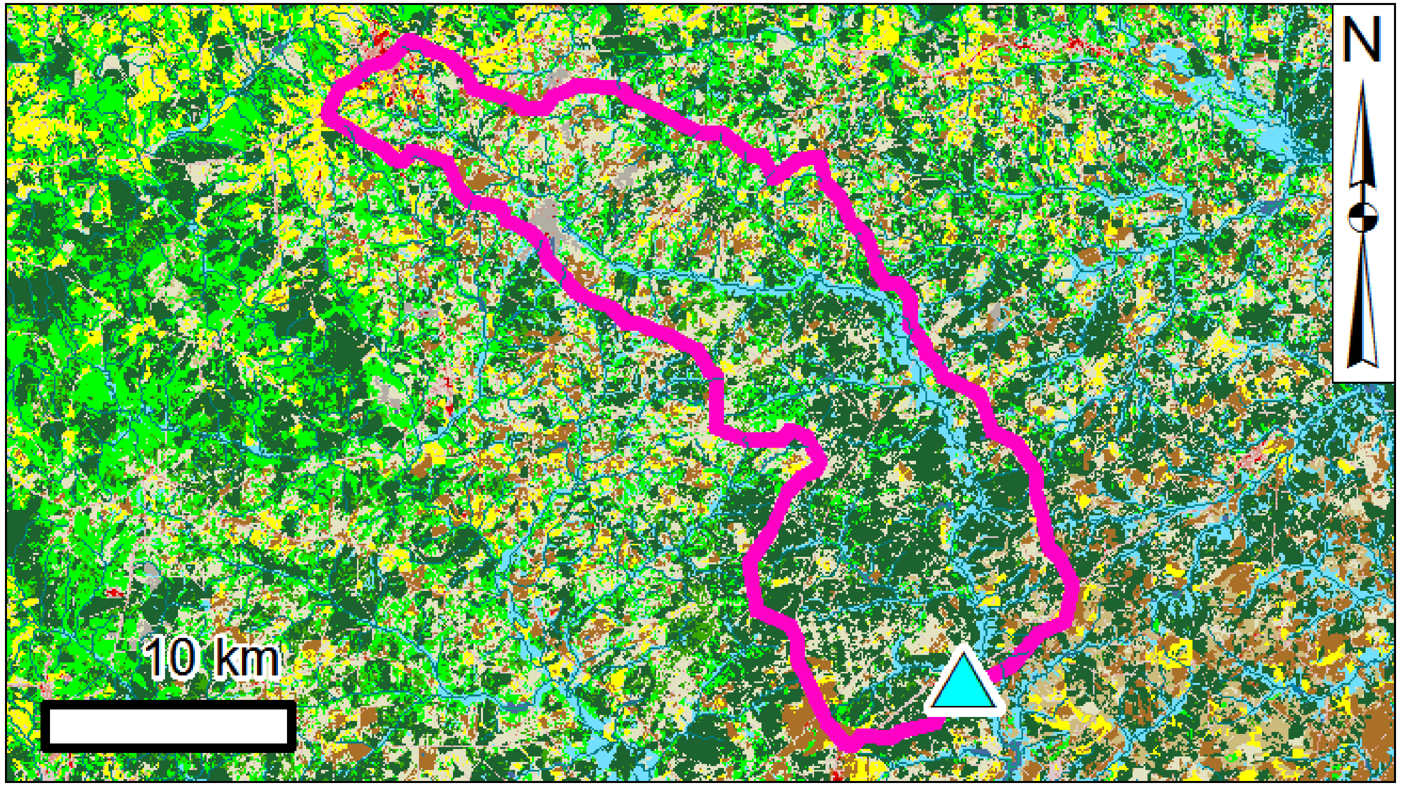
More information: *cohesivefire.nemac.org*

Source: National Association of State Foresters (NASF), National Fire Incident Reporting System (NFIRS), Federal Fire Occurrence Dataset, RSAC MODIS Hotspots


Transpiration
+
Canopy cover
+
Canopy interception
+
Canopy evaporation
-
Throughfall
-
Wildfire
+
Ash
+
Snow melt
-
+/-
+
Soil surface sealing
-
Infiltration
+
-
Shallow subsurface runoff
Overland flow
+
+
Soil water repellency
+
Baseflow
+
+
Storm flow
+
Surface hydraulic connectivity
+
+
Streamflow

Cohesive Strategy

- 2009 Federal Land Assistance Management and Enhancement (FLAME) Act:
  - Driven by growing wildfire suppression cost
  - Emphasizes need to allocate funds for broader implementation of hazardous fuel reduction projects across fire prone landscapes (prescribed fire, forest thinning)
  - Priority area: forests in wildland-urban interface
- Implementation: National Cohesive Wildland Fire Management Strategy ("Cohesive Strategy")
  - Nation-wide collaboration between GOs and NGOs
  - Minimize potential fire risk to people/fire hazard
  - Assist decision making with regard to prescribed fuel treatments
  - Enhance resilience of forest watersheds
  - <u>Maximize municipal water supplies</u>



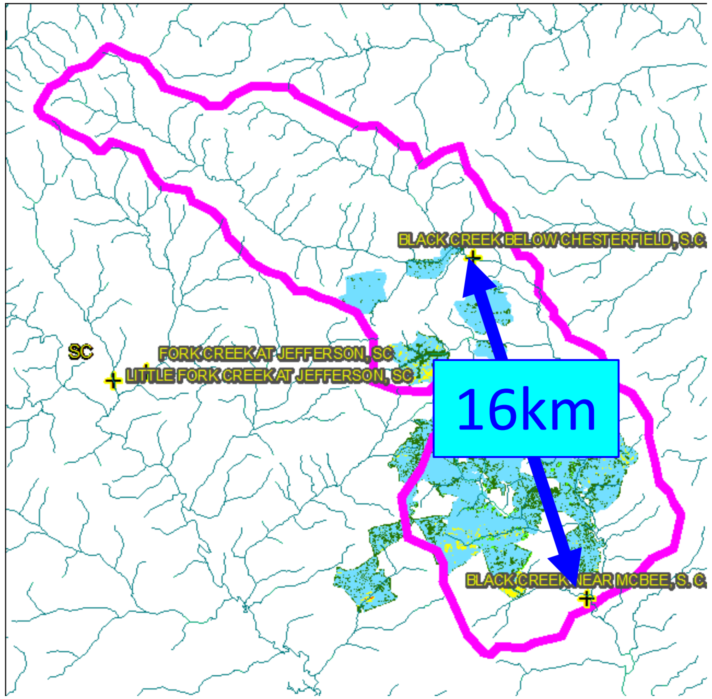
Southern Appalachian Piedmont Section

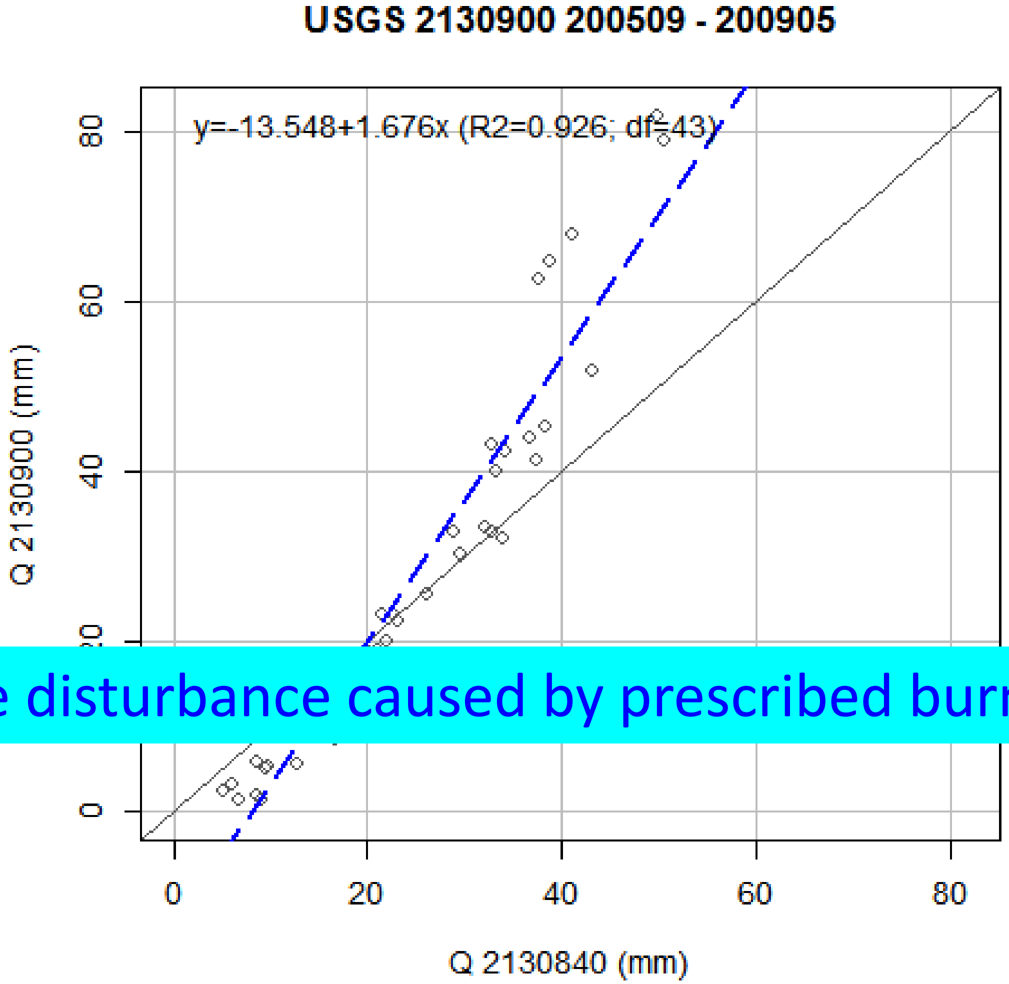
- Evergreen Forest (33%), Longleaf pine
- Grassland/Herbaceous (21%)
- Woody wetlands (11%)
- Deciduous Forest (10%)

Source: National Land Cover Database 2001

Black Creek (SC) / Prescribed burning

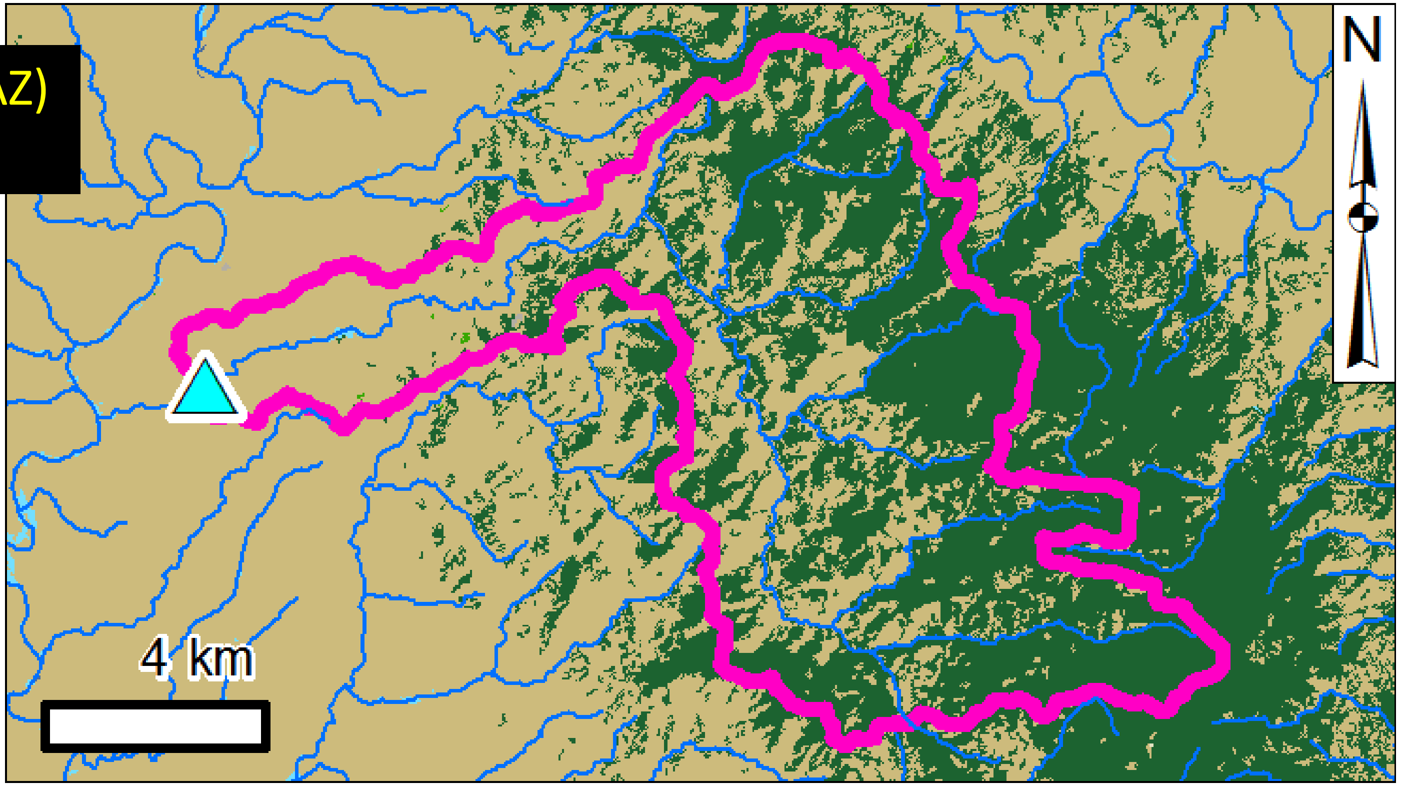
Strong correlation between monthly streamflow of adjacent stations (R^2=0.926), <u>high confidence in flow data</u>





Was the disturbance caused by prescribed burning?

Wet Bottom Creek (AZ)
2004 Willow Fire

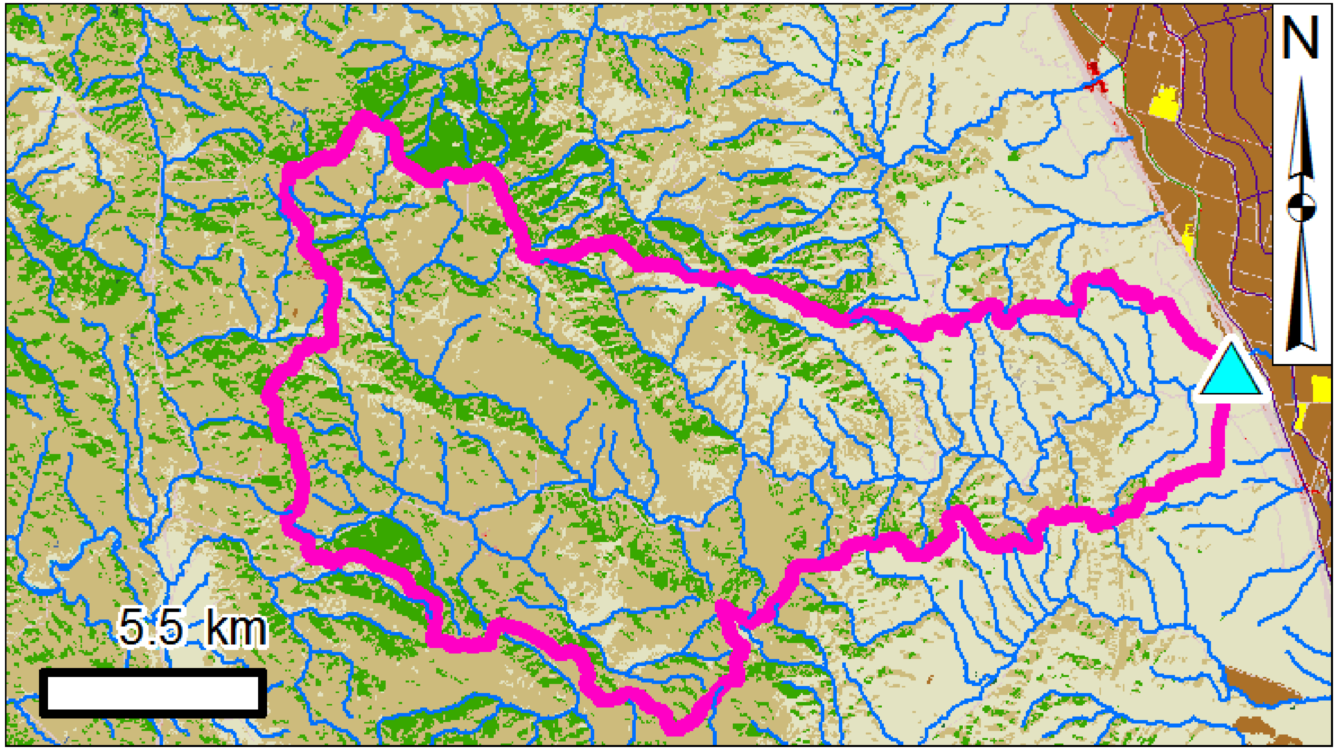


Tonto Transition Section

- Hill tops: Evergreen Forest (57%), Pinyon-juniper and Ponderosa Pine
- Shrub/Scrub (43%), chaparral

Source: National Land Cover Database 2001

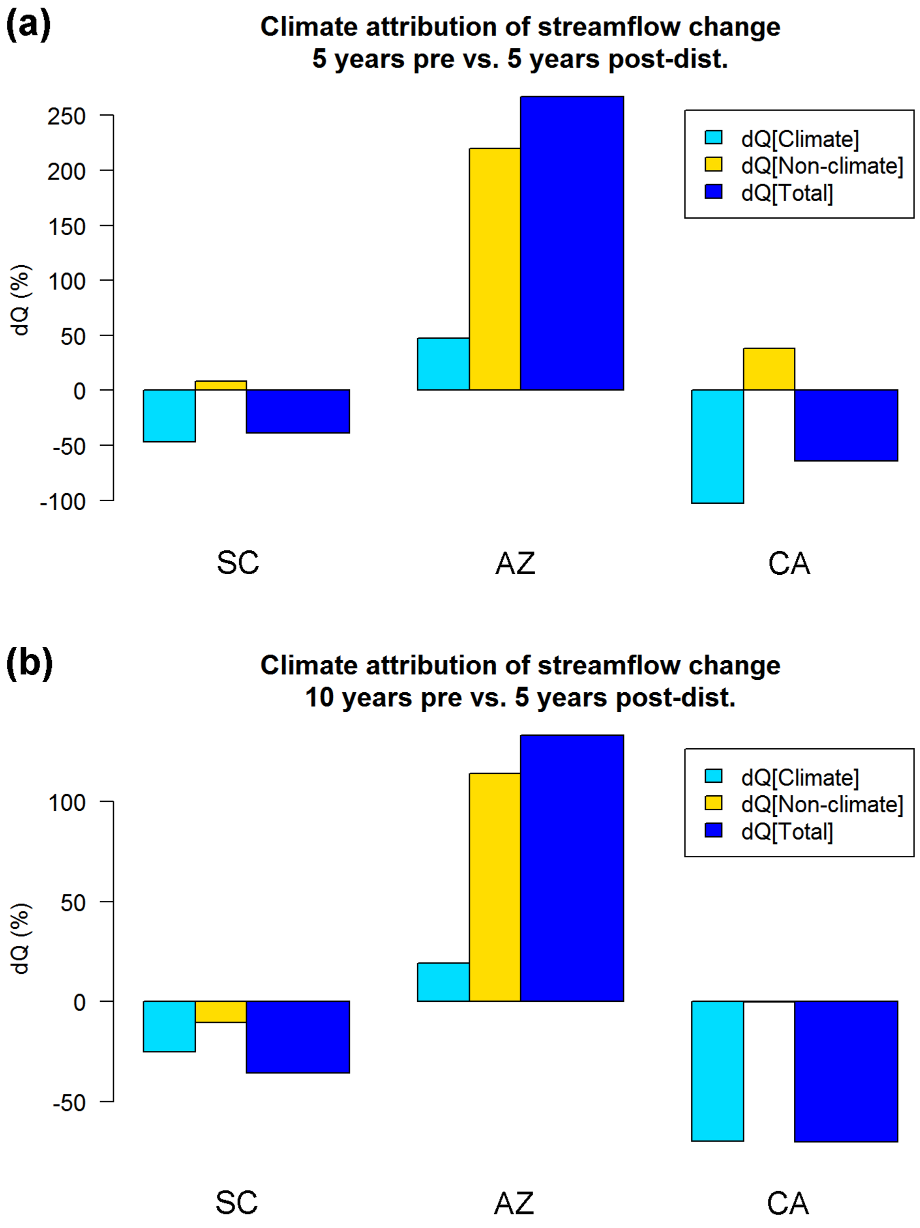
Del Puerto Creek
(Central coast, CA)
2003 Deer Park Fire



Central California Coast Ranges Section

- Shrub/Scrub (57%), California sagebrush, chaparral
- Grassland/Herbaceous (28%)
- Mixed Forest (14%), pine oak, eucalyptus
- Tree cover 25-50%

Source: National Land Cover Database 2001


(a)
Climate attribution of streamflow change
5 years pre vs. 5 years post-dist.
250
200
150
100
50
0
-50
-100
dQ (%)
dQ[Climate]
dQ[Non-climate]
dQ[Total]
SC
AZ
CA
(b)
Climate attribution of streamflow change
10 years pre vs. 5 years post-dist.
100
50
0
-50
dQ (%)
dQ[Climate]
dQ[Non-climate]
dQ[Total]
SC
AZ
CA

Bayesian Information Criterion

$$BIC = -2\ln(L_k) + k\ln(n)$$

Attribution of annual streamflow change (55 watersheds burned >10%)